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A SURVEY OF ELECTROFORMING FOR FABRICATING STRUCTURES

Revised Edition

by

W. H. Safranek

October 1964



FOR YOUR RETENTION

Redstone Scientific Information Center



U S ARMY MISSILE COMMAND
REDSTONE ARSENAL, ALABAMA

Contract No. DA-01-021-AMC-203(2)

Battelle Memorial Institute

Columbus, Ohio

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Research Branch
Redstone Scientific Information Center
Research and Development Directorate
U. S. Army Missile Command
Redstone Arsenal, Alabama

ABSTRACT

SEVERAL HIGH-STRENGTH STRUCTURES HAVE BEEN PRODUCED BY ELECTROFORMING, FOR SPECIFIC MISSILE AND AEROSPACE APPLICATIONS. SEVERAL ORGANIZATIONS HAVE ELECTROFORMED NICKEL WITH ULTIMATE TENSILE STRENGTHS OF 90,000 TO 100,000 PSI, OR MORE. TOUGH (NOTCH INSENSITIVE), 200,000-PSI NICKEL HAS BEEN ELECTROFORMED BY ONE OR TWO ORGANIZATIONS, BUT ADDITIONAL INFORMATION MUST BE DEVELOPED BEFORE SUCH A HIGH STRENGTH MATERIAL CAN BE ELECTROFORMED CONSISTENTLY IN A COMPLEXLY SHAPED FORM. THIS STATE-OF-THE-ART REPORT DESCRIBES ADVANTAGES AND LIMITATIONS OF ELECTROFORMING, SUMMARIZES AVAILABLE PROPERTY DATA OF MATERIALS, AND DISCUSSES ELECTROFORMING CONDITIONS THAT MUST BE MAINTAINED FOR GOOD CONTROL OF STRUCTURAL PROPERTIES.

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Section I. INTRODUCTION

Electroforming, first employed 120 years ago for producing printing plates and art forms, has emerged as a practical fabrication procedure for structures. Applications have been more extensive than is generally

realized in the engineering profession. This survey was undertaken to determine the advantages, scope, and limitations of electroforming as a practical and economical method for fabricating structures.

Section II. SUMMARY

Diverse and numerous applications for electroforming have been noted more recently in the engineering literature, and additional applications have been described in responses to a questionnaire circulated to organizations engaged in electroforming.

In typical case histories, better structures have been obtained at a lower cost by electroforming than with other fabrication methods. Pinhole-free structures with good density and strength have been produced by electroforming. Unlike free-standing bodies formed by plasma arc, electrophoresis, and other molecular-deposition methods, electroformed structures do not require compaction for densification.

Nickel, a metal that has usually been selected for electroformed structures, is the strongest material electroformed at the present time. The ultimate and yield strengths over the temperature range of about -423 to 1000 deg. F for some nickel specimens electroformed in sulfamate solutions are similar to those of the popular grades of stainless steel. A tensile strength of about 200,000 psi with no notch sensitivity can be obtained with a sulfur content of 0.01 to 0.017 percent, but a higher sulfur content causes a reduction in the tensile strength of notched specimens. For tough (notch insensitive) structures at cryogenic temperatures, the maximum sulfur content of nickel appears to be 0.01 percent. The tensile strength of such nickel at -423 deg. F was about 300,000 psi. Sulfur is incorporated in the nickel as sulfide, and originates from sulfur-bearing organic compounds originally added to reduce stress.

Electronic gear, molds, reflectors, electrotypes, and certain other specialties have been produced by electroforming for many years, but the control of properties important for structural items has not yet reached a truly satisfactory level on an industry-wide basis. Improvement in the control of properties is mandatory if the demand for electroformed structures continues to grow. Also, supplemental property data must be developed, and the conditions for producing electroformed structures need to be correlated in detail with the property values developed for the material. Reported data show only a general correlation with the type of solution, temperature, and electrical current density. Property data for nickel electroformed in like solutions at the same temperatures, using the same levels of electrical current density, span a broad range, which shows that unreported factors greatly influenced the properties of

the metal. Factors overlooked or disregarded in many instances included the concentration of the addition agent, the concentration of metallic impurities and of suspended particulate matter, filtration rate, and agitation rate. Vendors of electroformed structures must accept the fact that good process controls have to be rigidly followed.

Property data are less extensive and detailed for electroformed than for rolled or forged metals, and engineering development is much farther advanced for conventional methods of fabrication than for electroforming. Yet the available property data for electroformed nickel and the information developed on electroforming techniques, provide a sound basis for commercial growth. A few organizations have used these data and this information successfully in supplying acceptable structures. In other instances, facilities, engineering, and/or instrumentation must be improved to maintain the necessary control. Some of the present commercial sources need personnel trained in metallurgy and/or engineering. One recent report¹⁰⁵ states that a special "in-house capability was established" for electroforming lightweight solar concentrators because "the required degree of process controls was not available" in shops using the electroforming process.

Businesses installing appropriate facilities and instrumentation for good control of properties must risk capital investments. They need assurance that the risk is reasonable. The fluidity of the demand from the industry (chiefly aircraft) supporting structural electroforming is clouding the risk question. Industries that can profitably make use of electroformed structures to solve problems in structural uniformity and homogeneity should expect to support, either directly or indirectly, the cost of installing the equipment and instruments required for high-quality, property-controlled electroforming. The risk element is too large for the relatively small organizations that are technically qualified for expanding and improving their electroforming facilities.

The development of property data and procedures for producing electroformed structures began only three or four years ago. Future development could match the advances made during the last ten years in developing high-strength steels. There are prospects for a tougher and stronger electroformed metal. Grain-size control by regulating the cathode potential during electrodeposi-

*References cited are given on page 25.

tion deserves study. Commercial organic addition agents exist for bright plating which do not contain sulfur, but which refine the grain size considerable. The influence of these agents on mechanical properties should be evaluated. A nickel alloy of cobalt, and perhaps manganese, might meet the need for a stronger tougher material. Electroformed nickel or nickel alloy with reinforced fibers and/or dispersed, submicron-sized particles of dispersed oxides is another possibility.

For producing structures with high strength at high temperatures, methods developed for electrodepositing alloys of cobalt or nickel and tungsten have been adapted for electroforming on a small scale. Procedures for electrodepositing these alloys and the dispersion-hardened metals that can be produced by electrodeposition have recently advanced to an engineering stage of development and show good prospects for future exploitation.

In appraising the potential of the electroforming process, electroforming should be looked upon as potentially useful for a large number of structural applications. Limitations that have been documented for some contours and shapes will require modifications in the designs that engineers are accustomed to make for structures produced by conventional fabricating procedures. These modifications will not always be major, nor will they

have a significant harmful influence on performance. Improvements in performance, and/or reductions in cost, have been reported when some design changes were introduced for eliminating certain features that are incompatible with the electroforming process.

Some organizations with experience in electroforming are more optimistic than others in predicting successful electroforming of a large variety of structural shapes. The not-so-optimistic opinions are based, at least in part, on experience with specifications requiring unnecessarily rigid dimensional tolerances for difficult-to-form contours which were "frozen" before an electroforming specialist was consulted. In such case, electroforming was not feasible or was too costly.

It may be possible to fabricate several missile components by electroforming to improve reliability and/or reduce costs. It might be feasible, for example, to electroform in one piece the pressure-tank segments for SATURN V, although facilities would have to be installed for handling such a large part. The appointment of a team of specialists, including engineers experienced in electroforming capabilities, and structural engineers with knowledge of property and performance requirements, is suggested to establish the feasibility of electroforming specific missile structures.

Section III. ELECTROFORMING CAPABILITIES

CHIEF ADVANTAGES

The capability of forming complex structural shapes with good dimensional accuracy, surface finish, and homogeneity of properties and structure is the chief advantage of the electroforming process. Many commercially electroformed, relatively thin-walled structures, and many prototypes produced in pilot quantities have replaced welded or brazed assemblies of deep-drawn or extruded sections. In these instances, structural strength has been improved, distortion has been eliminated, and costs usually have been reduced. For high-precision geometry, as required for solar collectors, electroforming appears to be unexcelled. Aluminum-faced, electroformed nickel solar collectors have proved more efficient than stretch-formed aluminum or cast plastic reflectors.⁴⁷

Electroforming thick-walled structures has competed successfully with forging. Tooling for electroforming such a structure costs generally only 5 to 10 percent as much as a forging die for the same structure.

By comparison with the multiplicity of operations required for fabricating complex shapes from sheet stock, the electroforming process is relatively simple. The chief steps in electroforming representative structures are shown in Figure 1. In typical cases, these operations replace rolling, shearing, stamping, drawing, spinning, swaging, welding, and/or brazing of stainless steel sheet. Thus, potential savings in tooling and labor are incentives for considering electroforming. A saving in materials costs is also usual, because scrap is greatly reduced in many cases, and completely eliminated in others.

Electroforming has been especially advantageous for fabricating up to a few hundred identical or nearly identical parts, particularly for the aircraft industry, because tooling costs, inevitably high for stamping, drawing, and other fabricating operations, are usually much lower for electroforming, but several examples can be cited in which several thousand identical parts have been produced by electroforming in preference to other methods of fabrication not only because costs were lower, but also because structural characteristics were improved. Also, changes in items subject to frequent design or dimensional changes sometimes can be made quickly and inexpensively by modifying the contour or dimensions of the mandrels employed for electroforming. These advantages have recently focused the atten-

tion of design engineers in the aircraft industry on electroforming in preference to other fabricating procedures.

The strength of many commercially electroformed structures has been comparable with the strength of the popular grades of stainless steel. For example, typical values for the yield strength of unalloyed electroformed nickel are in the range of 55,000 to 75,000 psi. Also, the superior corrosion resistance of nickel compared to stainless steel has been advantageous for some applications.

DIMENSIONAL, SHAPE, AND FINISH CAPABILITIES

Structural applications for electroforming that are described in the literature are listed in Table I. Electroformed structures described in communications from organizations engaged in electroforming are given in Table II. Dimensions and finishes are detailed in Tables I and II.

SIZE CAPACITIES

The largest dimension of most of the structures produced by electroforming has been 6 feet, but some larger parts have been produced. The largest dimension that has been reported in the literature is 21 feet. Capabilities of shops engaged in commercial electroforming are limited to a length of about 25 feet or a diameter of 10 feet. Two vendors indicated plans for installing tanks large enough to electroform 30-foot-diameter parts. Others have pointed out that no size limit really exists if the demand justified the installation of larger equipment.

DIMENSIONAL ACCURACY

A dimensional accuracy of 0.002 to 0.005 inch is relatively easy to obtain for small or large parts, but a greater tolerance (up to perhaps 0.010 inch) is sometimes necessary for some dimensions of very complex shapes which require the use of expendable mandrels made of wax, plaster, low-melting alloys, or flexible rubber. As a rule, a 0.001- or 0.002-inch tolerance is maintained with expendable plastic mandrels or permanent, reusable metal mandrels. Distortion beyond these tolerances has been encountered in the past when the internal stress in the electroformed metal was not controlled at a low level (below about 5000 psi). Organizations engaged in electroforming are now aware of the

importance of stress control to avoid such distortion.

A dimensional accuracy of less than 0.001 inch has been obtained for some not-too-large or not-too-complex shapes. In such cases, the costs of making the mandrels have been greater than they would have been for making mandrels with larger dimensional tolerances.

WALL THICKNESS

The wall thickness of most structures produced by electroforming ranges from 0.010 to 0.050 inch. For lightweight solar concentrators, 0.002- to 0.004-inch walls have been generally produced, and for one experimental 21-inch prototype, the wall thickness was only 0.0013 inch.⁶⁰ Several objects with a wall as thick as $\frac{3}{4}$ inch or more have been electroformed.

With anodes that conform, or partly conform, to the shape of the mandrel, wall-thickness variations are restricted to between 5 and 20 percent on where variations of 100 percent, or more, would occur with ordinary anodes. Conforming anodes are particularly appropriate for articles with large, recessed areas, and can sometimes be used without excessive cost.

Electrical current shields placed over corners and edges reduce the wall thickness at those places and increase the thicknesses in holes and recessed areas, thereby improving thickness uniformity. Good uniformity of wall thickness is possible with plastic or plastic-coated steel shields integrated with the electroforming fixture. It is understood that nickel-thickness variations on the bellows convolutions ($\frac{1}{8}$ inch deep by $\frac{1}{8}$ inch wide) of expandable joints is restricted to only 15 percent by employing shields.

The nonuniformity in wall thickness reported for some CENTAUR bulkheads¹⁴ probably could have been decreased to ± 0.001 inch if conforming anodes had been used, or if openings had been cut into a plastic shield to equalize the current distribution to all areas of the hemisphere.

Shields permit controlled wall thickness when variation is desirable. For example, on electroformed nickel cones used for measuring heat transfer in a Mach 6.8 airstream, thickness has been graded with an accuracy of 0.001 inch, from 0.005 to 0.025 inch.¹²⁷

SURFACE FINISH

A surface finish of 8 to 16 rms microinches has been fairly common for the mandrel side of electroformed shapes. A better finish (2 rms microinches, for example) has been obtained for some objects when the identical finish was applied (at a premium cost) on the mandrel surfaces.

For thin-walled objects, the exterior surface finish is usually the same, or nearly the same, as the mandrel side. A 16 or 32 rms-microinch finish is practical for

any shape with a wall thickness of 0.1 inch, or less, by maintaining good filtration, anode diaphragming, and agitating facilities. Particle roughness that is difficult to avoid with a wall thickness of $\frac{1}{4}$ inch or more must be removed by polishing, grinding, or machining. Procedures for machining and grinding electroformed nickel have been examined.²⁵

DESIGN LIMITATIONS AND MANDRELS

The relatively poor distribution of electrical current at different areas on complex shapes limits electroforming of certain contours and shapes, even when specially shaped anodes are employed to equalize the current distribution as much as possible. Deep and narrow recesses in mandrel surfaces receive much less current and less thickness of metal than the surfaces lying closer to the anodes, for example. While specially shaped anodes can be inserted in the recesses to compensate, at least in part, for the unequal current distribution, recessed areas narrower than about $\frac{3}{4}$ inch would require complex and costly anode fixturing that would greatly limit the practicability of the process. The depth of a recess with a width less than $\frac{3}{4}$ inch should be not more than 30 or 40 percent of the width if economical factors do not justify complex and costly fixturing.

The limiting depth-to-width ratio for a narrow recess depends on the radii specified for angles between planes. A generous radius is recommended wherever it is acceptable on a performance basis. Inside right angles with a radius of less than about 0.03 inch are not practical, because the metal that is formed in such angles is structurally unsound.^{39,55,56,63,77,83,89,104} Acute angles with sharp corners result in voids in electroformed metals with a columnar grain structure.⁶⁴ Specially shaped anodes do not overcome these difficulties, but grow-ins, or preformed inserts, can usually be employed, at a premium in cost, to accommodate sharp right angles or acute angles, if they are necessary.

Metal distribution on complex shapes, and improved filleting in inside angles, can be obtained by periodically reversing the direct current when electroforming copper, deposited in cyanide solution, but periodic current reversal provides no such benefit when electroforming nickel.¹⁰⁴

Several authors have regarded as limiting features sharp angles on exterior surfaces opposite the mandrel side of the electroformed structure. While larger radii on exterior angles doubtless facilitate electroforming with minimum cost, metal can be deposited around sharp angles without excessive thickness or roughness by using electric current shields to limit the current distributed to corner areas. Very uniform thicknesses have been

obtained for objects with sharp right angles by using plastic rods to shield the corner areas from a part of the electric current. The optimum diameter and placement of a plastic rod (or tube) depends on the desired wall thickness.³⁹ Some commercial electroformers are now taking advantage of not-too-costly current shields for improving thickness uniformity. Shielding will undoubtedly be more widely used in the future.

Plastic shields, closely fitted to the ends of mandrels used to form cylindrical objects having one or two open ends, will prevent excessive thickness and roughness near the open ends. Plastic shields are used for hemispheres.

The complexity of the shape affects the selection of the material used for mandrels, which affects costs. Permanent, hard-surfaced mandrels are useful for cylinders, hemispheres, and other shapes with no undercuts or reentrant angles. When the number of parts to be electroformed justifies the fabrication of such mandrels, usually result in keeping costs lower.

Permanent mandrels with fusible coatings of tin or graphite-wax mixtures can be used for parts requiring no draft or having undercuts up to 0.0005 inch deep. The part is removed by pulling it away from the mandrel while the coating is melted, and the mandrel must be resurfaced after each cycle.

Destructible mandrels must be used for complex shapes having large undercuts or concave sections. Materials for destructible mandrels include both lacquered plaster (broken out mechanically), plastic and low-melting lead alloys (melted out), and die-casting alloys of aluminum or zinc (dissolved chemically). Parts made on such mandrels are usually the most expensive.

Nonmetal mandrels must be metalized to make their surfaces conductive. Silver deposited by chemical reduction has replaced graphite as the surface-conducting film employed in the electrotyping industry, but graphite and graphite-wax mixtures are still used for small lots of parts with complex shapes. Electroless copper or nickel have been useful for metallizing nonconductors. It is noted that silver has been deposited by the vacuum process for metallizing glass mandrels employed for electroforming small, experimental solar concentrators.⁸⁰

Many materials have been employed for permanent or destructible mandrels and for metallizing the nonconductors. These are described in several literature references.^{13,43,44,73,92,106} Metal and glass mandrels have been evaluated for solar concentrators,⁸⁰ and a subcommittee (VII) of ASTM Committee B-8 has balloted on a recommended practice for the processing of mandrels for electroforming.

Materials for mandrels, heat exchangers, agitators, and other equipment must be selected with care. To illustrate this need, amines leached from incompletely

cured epoxy-filled mandrels embrittled nickel bulkheads electroformed for CENTAUR structures.¹⁴ Metallic impurities such as iron tend to reduce ductility and increase stress, and can reduce dimensional accuracy.

PREFORMED INSERTS

Many of the limitations that were at first imposed on designers of electroformed articles were later overcome by the use of preformed inserts that are integrated with the electroformed object. Tables I and II list several examples. Figures 2 and 3 show how some of these inserts, or grow-ins, were incorporated with the electroformed structures. Inserts have been proposed for reinforcing structural beams.⁹²

In some instances, the inserts have been fabricated separately by an electroforming procedure before being attached to the mandrel prepared for electroforming the structural unit. In other cases, inserts have been machined from bar stock. The bond that can be obtained between nickel inserts and electroformed nickel structures is equally as strong or stronger than the nickel. Any bond failures encountered in practice can be attributed to an improper selection of cleaning and activating procedures.

Inserts must be tightly fitted against the mandrel and aligned carefully. If a gap of more than 0.001 inch exists between insert and mandrel, or if the insert and mandrel are aligned on different planes, the strength of the electroformed article will be reduced there, and cleavage might occur during the final separation step. Gaps of the order of 0.0005 inch or less are strongly bridged with a wall thickness of 0.015 inch or more. Preformed flanges and segmented mandrels must be as closely fitted as inserts.

Strength of the joint over adjacent, preformed inserts usually is about the same as the strength of a welded joint. For example, bond strengths of 59,000 psi for electroformed nickel joined to unhardened steel inserts have been reported. No heating is required during electrojoining, so the strength and dimensions of the inserts can be preserved without the damaging heating effects that can occur during welding or brazing. Inserts employed in electroforming have included metals, plastics, ceramics, cermets, and quartz.

ELECTROFORMING RATES

Rates for electroforming structural components usually range from 0.002 to 0.005 inch/hour, except for relatively simple shapes that can be formed at 0.01 to 0.02 inch/hour with higher-than-normal current densities. For thin-walled structures, less than about 0.04 inch, a rate of 0.003 to 0.005 inch/hour is fast enough

to complete the electrodeposition process in a normal working day. Thicker walled structures must be electroformed during off hours, when good attention to all factors influencing properties might be lacking. Several

of the questionnaires returned from commercial sources pointed out that a higher electroforming rate was needed to make the process more practicable.

Section IV. METALS, ALLOYS, AND SOLUTIONS FOR ELECTROFORMING

COPPER, IRON, AND NICKEL

Copper, iron, or nickel usually are selected for electroforming because they are low in cost and because electrodeposition procedures have been further advanced for these metals than for others. The copper sulfate-sulfuric acid bath is customarily selected for electroforming copper. Nickel is the most useful of these metals for structures because it is much stronger than copper and is both stronger and more ductile than electrodeposited iron. Property data for these metals are detailed later in this report.

For electroforming nickel, high-concentration nickel sulfamate solutions at about 125 deg. F are preferred for high-strength (>100,000 psi) structures. A temperature of 140 deg. F improves ductility and minimizes stress. Organic addition agents containing sulfur increase tensile strength to about 200,000 psi, but use must be controlled to avoid brittleness and notch sensitivity. Sulfide embrittlement resulting from these addition agents is particularly evident after heating the electroformed structure to 500 deg. F, or higher.

NICKEL-COBALT AND NICKEL-MANGANESE ALLOYS

Alloy containing 50 to 70 percent nickel and 50 to 30 percent cobalt, which can be deposited in sulfate-chloride or sulfamate baths,³¹ has been used for electroforming a few shapes. The alloy has received less attention than it deserves, in view of the encouraging data available on its tensile strength—150,000 to 200,000 psi without organic additive agents.

Nickel-manganese alloy with a tensile strength of 180,000 psi has been reported.¹⁰⁹ No supplemental data are available, but it is understood that the manganese content was about 2 percent and that the alloy was electroformed in a nickel sulfamate-manganese sulfamate solution.

CHROMIUM AND CHROMIUM ALLOYS

The development of a satisfactory procedure for electroforming chromium or chromium alloys has been the goal of several research projects, and the electrodeposition literature includes at least fifty references to electrodeposited "stainless steel." Attempts to thicken either unalloyed chromium or iron-chromium-nickel alloys to produce structural items have been unsuccessful

because the deposits became too highly stressed and cracked.

A crack-free chromium alloy containing about 10 percent iron has been electroformed experimentally in a trivalent chromium solution, and some property data have been developed.⁹⁴ However, the alloy was too brittle to meet the requirements for structural applications, and the throwing power of the electrodeposition bath was not sufficient to provide complex shapes without accurately conforming anodes.

A few not-too-complex-in-shape articles have been electroformed by depositing alternate layers of nickel and chromium, with the objective of achieving good oxidation resistance at elevated temperatures. Some property data have been developed for a nickel-20 percent chromium alloy produced by diffusing multiple, alternate layers of nickel and chromium.⁹⁴ Experience with this diffusion alloy as a protective coating at high temperatures¹¹⁰ presages favorable characteristics for some electroforming applications.

The procedure used experimentally for producing a diffusion alloy of nickel and aluminum³⁰ suggests a method of electroforming a nickel-chromium-aluminum alloy.

HIGH-STRENGTH ALLOYS AT HIGH TEMPERATURE

A dense alloy of cobalt and 35 to 45 percent tungsten was electroformed in a high-temperature, ammoniacal solution about 20 years ago,³⁰ and this alloy has been re-examined recently for electroforming applications in several laboratories. The alloy must be deposited under carefully controlled conditions to avoid excessive stress and cracking, and must be heat treated to induce sufficient ductility to withstand machining or finishing operations. A 35 percent tungsten alloy exhibited high strength at high temperatures (18,000 psi at 2200 deg. F),¹⁹ but its strength at about 70 deg. F was about the same as that of the relatively ductile nickel electroformed in nickel sulfamate solutions containing no additive agents for increasing strength or reducing stress.

Dense and coherent cobalt alloy containing 60 to 65 percent tungsten was electrodeposited about ten years ago while the direct current was interrupted for 1½ seconds during each 2½-second cycle,⁴⁸ but no record of electroforming applications was identified.

The prospect of developing a procedure for electroforming a super-strength alloy at high temperature was

recognized four years ago by several specialists.^{41,102} One approach examined during a recent three-year research program was based on dispersing fine particles of a chromium-tungsten-aluminum-titanium master alloy in electrodeposited nickel and "solutionizing" the particles during heat treatment at about 2000 deg. F.^{19,20,21} The tensile strength at room temperature was 49,000 psi for an alloy containing about 25 percent of these alloying constituents, and only 5,800 psi at 1800 deg. F.

Another approach to the development of a procedure for electroforming tough structures for high-temperature applications was conceived about five years ago.^{46,124} In this approach, small particles of oxides or carbides were dispersed in electrodeposited metals by several investigators,^{42,45,124,125} and one¹⁹ reported a tensile strength of 3,300 psi at 2,000 deg. F and an elongation of 34 percent for nickel containing 30-micron particles of alumina. Relatively little attention has been given to the dispersion of submicron-sized particles which are needed for effective dispersion strengthening, but yield-strength data for nickel containing 0.02-micron particles of alumina were encouraging.⁹⁹

The feasibility of controlling the dispersion of >0.1-micron, bath-insoluble particles in large electrodeposition solutions has been demonstrated on a commercial scale for decorative-plating applications.^{78,115} Thus, applications for electroforming with dispersions of the submicron particles are worthy of further investigation.

One-mil-diameter tungsten wirements have been used for increasing the strength of electroformed copper to between 160,000 and 205,000 psi.¹²² The copper contained 25 to 35 percent, by volume, of the tungsten fibers. Such tungsten-wire reinforcement offers prospects for improving both the room- and high-temperature properties of electroformed nickel.

REFRACTORY METALS

Columbium has been electroformed in fused, mixed fluoride baths operated at about 1400 deg. F by a process announced in 1963.^{54,68} Wall thickness has been built up to ¼ inch. Densities were reported to be 99.8 percent or more of the theoretical density, but no mechanical-property data were reported. The process might be useful for complex shapes because the throwing power of the bath is said to be better than that of commercial

nickel solutions. Electroforming of columbium and tantalum is offered commercially.¹¹⁷

Tungsten was electrodeposited in a dense, consolidated form up to a thickness of 0.016 inch in a fused alkaline-salt bath at 1500 to 1650 deg. F.⁶⁷ Use for electroforming does not appear feasible, because the metal deposited in excess of a 0.016-inch coating was particulate.

Dense electrodeposits of molybdenum were claimed recently for electrolysis at 1850 deg. F of a molten bath of molybdenum oxide, sodium pyrophosphate, sodium chloride, and sodium borate.¹²⁸

For electroforming applications of any high-temperature, fused-salt deposition process using a refractory metal, copper, nickel, steel, or another metal with a higher melting point would have to be used as a mandrel.

SILVER, GOLD, AND RHODIUM

A composite of silver or gold, and either copper or nickel, has been useful for electroforming high-frequency radar waveguides. A few structural applications have been considered for gold and gold alloys because a tensile strength of >35,000 psi has been obtained for very lowly stressed, ductile, 99.9+ percent gold deposited in acid cyanide baths. Gold alloys containing 1 percent nickel and/or cobalt probably would be even stronger, based on hardness data.

With present-day procedure for electrodepositing rhodium, this metal is too highly stressed and brittle to fabricate electroformed structures. A project was started in 1963 to determine the feasibility of electroforming rhodium seals.⁷

ALUMINUM

Two organic solutions have been employed experimentally for electroforming aluminum.^{16,96} In each case, costly precautions are necessary to prevent water contamination from humid air. The aluminum chloride-lithium hydride-ether bath^{16,29} has been used on a semi-commercial scale for electroforming radar waveguides and reflectors. The most recent application for electroformed aluminum is classified information. Experiments are being conducted with aluminum reinforced with fine beryllium wire and with alumina dispersion-strengthened aluminum.¹²⁵

Section V. PROPERTIES OF ELECTROFORMED METALS AND ALLOYS

PHYSICAL AND MECHANICAL PROPERTIES AT ROOM TEMPERATURE

The physical properties of the relatively popular electroformed metals are given in Table III. The minimum density values here correspond to structures that contained pores or voids. The maximum values closely approach or exceed the *ASM Handbook* values for dense, annealed metals.

Room-temperature strength and ductility data for the metals and alloys commonly selected for electroforming are given in Table IV. Minimum, maximum, and a typical or nominal value are given in the table for each metal or alloy. The minimum and the typical strength values correspond to specimens produced without organic addition agents which are fairly common in electroplating applications for refining grain structure (brightening), hardening, or reducing stress. The data in Table IV detail the properties for metals with a wall thickness of 0.02 inch, or more. Significant differences have been reported for very thin-walled electroformed metals (0.002 inch, or less).

The current density, the temperature, and the composition of the electrodeposition solution and other factors influence the properties of the electroformed metal. Addition agents for grain refining frequently have a profound effect. For example, a two- to three-fold increase in the ultimate tensile strength can be obtained with specific additives to either copper or nickel electrodeposition baths.

The maximum strength values in Table IV have been reported in the literature for electroformed metals produced with organic addition agents. Reducible sulfur-containing additive agents, which are popular for nickel plating, should never be used for electroforming articles that will be heated to a temperature of 500 deg. F or higher, because included sulfides greatly reduce the ductility of the material (copper or nickel). Sulfated, straight chained, alcohol derivatives do not ordinarily contribute sulfur to electrodeposited nickel, and are considered essential for reducing the surface tension of the bath and preventing pitting. Such a wetting agent was very effective in eliminating pitting, reducing internal porosity, and refining the grain structure of electroformed cobalt-tungsten alloy.¹¹⁶

The physical and mechanical properties of electroformed nickel are related to the type of solution and

conditions of deposition. Typical properties for nickel formed in four solutions are given in Table V. Stronger nickel with a higher yield strength is obtained with the nickel chloride and nickel sulfamate solutions than with the other solutions. The sulfamate bath is the most popular, not only because its deposits are strong, but because they exhibit less stress (without organic stress-reducing agents) than those produced in the other baths. Nickel electroformed in the chloride bath is highly stressed, which sometimes causes distortion or warpage.

Nickel, with an ultimate tensile strength of about 90,000 to 110,000 psi and a yield strength of 60,000 to 78,000 psi, has been electroformed by several sources in a nickel sulfamate solution containing no organic stress-reducing agent. Elongation in 2 inches for these specimens ranged from about 6 to 14 percent. Although no stress reducer was added, the stress level probably was relatively low, below 9,000 psi in tension, because solution temperatures were in the range of 120 to 135 deg. F.

Nickel, with an ultimate tensile strength of about 200,000 psi and a yield strength of about 100,000 psi, was formed in nickel sulfamate solutions containing a stress-reducing agent (saccharin or trisulfonated naphthylene) and maintained at a temperature in the range of 115 to 125 deg. F. Tensile and yield strengths were reduced when the temperature of the electroforming bath was increased, as shown in Figure 4.^{50,51} A current density of about 30 to 40 amp/sq ft was employed for these tensile specimens.

The strength of the nickel is influenced by the amount of stress-reducing agent added to the nickel sulfamate solution. Figure 5 compares tensile strength values for electroformed nickel as a function of the sulfide content of the material.^{50,51} High strength was obtained consistently when the sulfur content was 0.012 percent, or more.

NOTCH SENSITIVITY

Comparison of tensile strength data for notched and unnotched specimens of nickel electroformed in the Watts-type solution without addition agents showed ratios of notch strength to tensile strength greater than 1, indicating no notch sensitivity (at room temperature) for the electroformed nickel. The notch and tensile strength data were as follows:⁹⁷

Nickel Thickness (mils)	Tensile Strength 10 ³ psi		Ratio of Notched to Unnotched Tensile Strength
	Notched (K _t = 5)	Unnotched	
85	74	69.5	1.07
58.6	59	58.6	1.01

A high ratio of notched to unnotched tensile strength values was also observed for a nickel electroformed in sulfamate baths when no stress-reducing agent, or only a relatively small amount, was added to the bath.^{49,50,51} Nickel with a high sulfur content, greater than 0.017 percent, was notch sensitive, whereas nickel containing <0.018 percent sulfur usually was not. The influence of the sulfur content on a series of 21 specimens is shown in Figure 6.

At -423 deg. F, nickel containing >0.010 percent sulfur was notch sensitive, as a rule. Yet high ratios of notched to unnotched tensile strength were observed for nickel containing 0.0005 to 0.01 percent sulfur. In Figure 7 the ratios are shown as a function of the sulfur content.

FATIGUE DATA

Krouse-type fatigue specimens machined from Watts-type electroformed nickel failed at 39 to 41 x 10⁶ cycles when the relatively fine-grained mandrel side of the specimens was subjected to a maximum tensile stress of 29,000 psi.⁹⁷ Specimens with the mandrel side subjected to a compressive stress failed at 8 and 27 x 10⁶ cycles. However, during a previous investigating, endurance limits for 10⁷ cycles for Watts-type nickel ranged from 30,000 to 44,000 psi.⁹⁷ Endurance ratios were approximately 0.5.

STRENGTH OF WELDED JOINTS

Data from one source⁸ for electroformed nickel weld showed strengths of 34,700 and 38,900 psi for TIG welds. Yield strengths were 19,110 and 25,100 psi, and elongations were 5.3 to 9.1 percent. Higher strengths, up to 68,800 psi but usually 38,400 to 44,700, were developed by another source for nickel-to-nickel butt welds.^{50,51} These values corresponded to a joint efficiency of about 40 percent. A higher joint efficiency of about 50 percent was obtained with stainless steel filler welds. Neither the joint-strength data nor the reported efficiency variations correlated directly with the sulfur or oxygen contents of the electroformed nickel; the available data are too limited to establish the effects of welding-procedure variations.

Higher weld-strength values also were reported for nickel-to-301 stainless steel joints: 50,700 to 59,800 psi for butt fusion weld and 59,800 to 72,400 for roll-

seam welds, corresponding to joint efficiencies of about 50 percent and 60 to 90 percent, respectively. The nickel was electroformed in sulfamate solutions in all cases, and contained 0.01 to 0.025 percent sulfur in some cases.

The weldability of electroformed nickel appears to be satisfactory for cryogenic applications if the concentration of stress reducer is below about 0.15 oz/gal,⁵¹ but weld efficiencies were lower in the case cited than the customary efficiency for stainless steel welds. An improvement in the nickel weld efficiency may be possible by modifying the welding procedure or by establishing the material factors that influence joint efficiency. The few high values (77 to 80 percent) reported in weld efficiency for a few individual specimens indicate that high efficiencies might be reproduced consistently if electroforming and welding operations were controlled effectively. Factors that must be controlled for reproducing a high efficiency must be established by research and development.

STRESS IN ELECTROFORMED METALS

Internal stresses in electrodeposited metals can cause warpage and dimensional changes (or cracking) when the electroformed part is separated from the mandrel. A high internal stress reduces the stress that can be applied externally during service. Thus, much effort has been given to development of procedures for eliminating internal stress or keeping it at a low level.

Copper electroformed in copper-sulfate baths is nearly stress-free when no additive agents are used in the solution. The highest stress reported by several independent investigators was only 4,000 psi.⁹²⁻⁹³ Periodic current reversal reduced the stress from about 2,000 to 1,400 psi for copper electroformed with one set of conditions.¹¹⁸ A high tensile stress—up to 21,400 psi—was reported for copper electroformed in solutions containing gelatin,³⁵ and a compressive stress (-8,000 psi) was observed when thiourea was added to the copper sulfate bath.⁵⁸

Values for stress in iron electroformed in a ferrous chloride-calcium chloride bath span a broad range, from 5,000 to 135,000 psi. To keep stress at a relatively low level (10,000 to 16,000 psi), a high temperature (195 deg. F or more) and a relatively low hydrochloric acid concentration is desirable.⁶⁵ Addition of saccharin to a ferrous ammonium sulfate-ammonium fluoborate solution operated at 140 deg. F reduced stress from about 9,000 to 1,800 psi.

Nickel electroformed in nickel chloride solutions is highly stressed. Stress levels usually are between 40,000 and 50,000 psi.³¹

Stress in nickel electroformed in Watts-type solutions usually ranges from about 16,000 to 24,000 psi, but levels up to 60,000 psi have been measured for nickel deposited in high pH solutions.⁷¹ A lower stress level—about 8,000 psi—can be achieved with good electrolytic purification for removal of iron and other impurities from the solution. Organic additive agents that keep stress at a low level (below 10,000 psi) include saccharin,¹¹⁹ cysteine hydrochloride,¹¹⁹ sodium benzene disulfonate,⁷¹ and p-toluene sulfonamide.¹²⁰

The low level of stress that is customary for nickel electroformed in sulfamate solutions is one of the reasons for the popularity of these electroforming baths; 500 psi is the lowest stress reported for nickel deposited in sulfamate solutions containing no chloride ions or organic stress-reducing agents.^{5,80,105} This low value was obtained in a 60-ounce bath operated at 140 deg. F with an average current density of 60 amp/sq ft, and it has been confirmed by others. A slightly higher stress was observed for nickel electrodeposited at a low current density (20 amp/sq ft) and a high current density (100 amp/sq ft). A decrease in the temperature of the electroforming bath, or the addition of chloride ions to improve nickel anode dissolution, causes an increase in stress.¹² A stress of 5,000 to 10,000 psi is customary for high-strength nickel (>100,000 psi) electroformed in sulfamate-chloride solutions containing no stress reducer.

A compressive or near-zero stress can be controlled with organic stress reducers. Trisulfonated naphthalene is effective for this purpose.³² Saccharin, p-toluene sulfonamide, and nickel dibenzene sulfonate also reduce stress.¹⁰⁷ An automated procedure has been described for regulating stress at a low tensile level with continuous addition of saccharin to a Watts nickel-plating bath.⁷⁹ The stress in nickel-cobalt alloy, which is relatively high without a stress reducing agent, can be reduced to a maximum of 7,000 psi in tension by adding saccharin.¹¹⁰ Additions of sulfur-containing stress reducers induces notch sensitivity if the sulfur content of the nickel exceeds about 0.017 percent, and will reduce ductility if the structure is heated, as noted previously in this report.

Stress in cobalt alloy containing about 30 percent tungsten was reduced from about 80,000 to only 17,000 psi by employing isooctyl phenyl polyethoxy ethanol as a nonionic wetting agent.

MECHANICAL PROPERTIES AT CRYOGENIC AND HIGH TEMPERATURES

Strength and ductility data for electroformed nickel at cryogenic and high temperatures were reported from several sources and are given in Figures 8, 9, and 10. The ultimate and yield strengths and elongation for nickel were generally much greater at -373 or -423 deg. F than they were at room temperature. But the elongation of nickel electroformed in a sulfamate bath containing a stress reducer was lower at -423 deg. F than it was at 70 deg. F. Curve 3 in Figures 8 and 10 and Curve 2 in Figure 9 for nickel electroformed in a nickel sulfamate bath were comparable with the data reported for nickel electroformed in a chloride bath.⁹⁷

Supplemental data for the properties at -320 deg. F for nickel containing <0.08 percent sulfur and electroformed in nickel sulfamate solutions containing no stress reducer were as follows:⁵⁷

Bath Temperature (°F)	Solution (pH)	Tensile Strength 10 ³ psi	Yield Strength 10 ³ psi	Elongation in 2 inches (percent)
120	3.5	101 to 122	59 to 89	9 to 16
120	4.5	133 to 141	83 to 87	7 to 8
140	3.5	104 to 157	62 to 96	4 to 14
140	4.5	145 to 153	90 to 98	8 to 12

Tensile-strength data for an alloy of cobalt with 35 percent tungsten, 2 percent iron, and 1 percent nickel are given in Figure 8, as a function of temperature. Tensile data from two sources^{19,116} show that cobalt alloy containing less than 30 percent tungsten is not as strong at elevated temperatures as the alloy containing >30 percent tungsten.

Stress rupture data have been reported for nickel electroformed in a Watts bath⁹⁷ and a nickel sulfamate bath.¹⁰⁸

Section VI. SPECIFICATIONS AND TESTS

SPECIFICATIONS

The specification on electroformed nickel prepared in 1962 for consideration for POLARIS fleet ballistic missiles²³ included three classes, as follows:

Class	Tensile Strength (minimum psi)	Elongation in 2 Inches (minimum percent)
1	15,000	20
2	60,000	10
3	100,000	4

Class 3 requirements appear realistic for structures that can be electroformed in nickel sulfamate baths with good control of solution composition, pH, temperature, agitation, and other factors.

Section B, Subcommittee VII*, ASTM Committee B-8*, is engaged in preparing a specification on electroformed metals. After it is prepared, it will be submitted to Subcommittee VII, Committee B-8 for balloting.

TESTS

MECHANICAL PROPERTIES

In some cases, specimens machined from areas cut from the electroformed part during the final trimming step are inserted in tensile-test machines. In others, special flat specimens are electroformed at the same time as a part or group of parts are electroformed. In this case, there is no assurance that the flat specimens are representative of the parts being electroformed. Tensile test specimens from trimmed stock are better samples.

EXTERNAL FLAWS

In addition to visual inspection, radiography, ultrasound, and eddy-current conductivity measurements have been employed for detecting flaws in electroformed

structures,³⁷ but these inspection methods are uncommon.

DELAMINATION TENDENCY

Transverse-section bending is useful for detecting weakly coherent layers that were electrodeposited with current interruptions or sudden large changes in bath composition or current density. Bending after heating at 1100 deg. F was proposed for electroformed nickel. This test seems more appropriate for detecting sulfur-embrittled nickel and, thus, might be more appropriate for eliminating embrittled nickel subject to a high-temperature service.

INTERNAL FLAWS AND INCLUSIONS

Microscopic examination (at 500 to 1000X) of sections from "trimmed" metal has been employed for detecting internal porosity and inclusion of foreign particles. Grain size, which also can be estimated with this procedure, provides information that is valuable in the absence of mechanical-property data.

DENSITY

No one seems to be checking density as a means of assaying acceptance, but density measurement would be a simple, useful test for screening electroformed material containing a large number of internal pores. Undesirable, thermally unstable inclusions can be detected by comparing density before and after heating.³⁴

PERMEABILITY

Helium pressure tests have been employed for checking permeability of pressure vessels, diaphragms, expansion joints, and other structures.

SPECULAR REFLECTIVITY

The specular reflectivity of solar concentrators was evaluated by spectrophotometer reflectance measurements.³⁰ Concentration efficiency was determined by making calorimetric tests.

*Subcommittee VII, A. D. Squitro, Chairman, includes approximately 75 members of vendor, purchaser, or general interest status.

Section VII. IMPORTANT FACTORS FOR CONTROL OF PROPERTIES OF ELECTROFORMED STRUCTURES

Many factors are known to affect the properties of electroformed metals. Important factors that should be controlled for electroforming nickel structures are outlined herein, by way of example.

MAJOR BATH CONSTITUENTS

The high concentrations of nickel salts desirable in the sulfamate bath for good smoothness and density (especially in low current density areas) can be adequately maintained by regular (weekly or biweekly) chemical analysis. This generally poses no special problem. Large fluctuations in concentration caused by large additions of water should be avoided by adding the water continuously, or at least hourly.

Acid concentration (pH) has a considerable influence on grain structure and stress and must be controlled within 0.5 pH unit for consistent results. A pH of 3.6 ± 0.3 is customary for the nickel sulfamate bath. A reduction in strength has been observed for nickel electroformed in a solution with a lower pH. Ductility is reduced for nickel electroformed at a high pH.

WETTING AGENTS AND SURFACE TENSION

Control of surface tension to avoid pitting does not always receive the attention it deserves. A wetting agent should be added to keep the surface tension near 35 dynes/cm, checked with a 50- to 60-drop stalagmometer. Other devices for checking surface tension have not always been reliable.

ADDITION AGENTS AND MECHANICAL PROPERTIES

Saccharin, sulfonated naphthylene, or another sulfur-containing compound sometimes is added to reduce and control stress. In view of the data reported recently^{50,51} on strength and notch sensitivity, the influence of these agents on the sulfur content of the nickel should be checked and controlled to avoid notch sensitivity. If stress in the nickel exceeds a tolerable limit when the sulfur content is controlled at a low, tolerable value, impurities (iron and other metals and organic contaminants) should be removed from the nickel bath by electrolytic purification and activated carbon treatment.

METALLIC AND ORGANIC IMPURITIES

Continuous electrolytic purification, activated carbon treatment, and filtration are rather commonly used for decorative plating, to remove impurities affecting the

brightness and smoothness of the nickel deposits. These treating procedures have not been adopted for electroforming to the extent that they have been for decorative plating, yet they are essential for good control of mechanical properties. Facilities for these procedures are nonexistent in some electroforming shops and inadequate in others.

TEMPERATURE

Personnel engaged in electroforming are generally cognizant of the importance of good temperature control and are usually assisted with automatic thermostat devices. These devices sooner or later fail, and defective work is the result when the failure is overlooked. Because electroforming is a slow process (as practiced now), requiring from 8 to as many as 250 hours, there is a special need for a better regulation device and/or a secondary warning or take-over system. Temperature changes cause large variations in the mechanical properties (tensile strength and elongation) and in the internal stress in electroformed nickel.

CURRENT DENSITY

The average current density for electroforming nickel in sulfamate solutions is in the range of 35 to 60 amp/sq ft, but the current density varies considerably (perhaps 5 to 150 amp/sq ft) at different surface areas of objects with complex shapes. Increasing use should be made of conforming or semiconforming anodes and current shields to insure better uniformity of mechanical properties and thickness at different surface areas of such shapes.

The design of effective conforming anodes and shields is largely empirical, but the "trial and error" approach gradually is being replaced by an accumulation of experimental data and experience. The charting of equipotential lines on a two-dimensional plane, based on current resistance measurements, has been used for establishing current relationships between anodes and cathodes.⁵⁰

AGITATION

Although agitation at cathode (mandrel) surfaces has considerable influence on the mechanical properties of electroformed nickel, little attention is given to it in some electroforming shops beyond installing a mechanical rocker or an air-bubbling device. The lack of quantitative data on the effects of variations in agitation

is a handicap in some instances, but profound effects are suspected. A difficulty exists in other cases in achieving uniform agitation at different areas of objects with complex shapes. Cathode potential measurements employed now as a research tool would be helpful for checking and controlling agitation effects. Engineering development is recommended for determining the usefulness of such measurements and adaptation to production control. A study could show that improvement in mechanical properties and/or electrodeposition rates would result if agitation rates were increased.

An increase in the average cathode current density above about 60 amp/sq ft is precluded at the present time for electroforming nickel, because anodes do not dissolve efficiently unless a large stress-inducing concentration of chloride ions is added to the bath. Agitation at anode surfaces is helpful for efficient anode dissolution and avoiding the injurious effect of sulfamate ion oxidation products. Effects at nickel anode surfaces probably could be monitored with anode potential measurements.

Section VIII. COMMERCIAL SOURCES AND CAPABILITIES

Excluding the many electrotypers, there are at least 25 commercial electroformers, some specializing in molds, electronic gear, or record stampers. About twenty have had experience with property-controlled structures; others expressed interest in structural applications.

Organizations that supplied information on facilities and capabilities are listed in Table VI; twelve of these furnished mechanical-property data representative of structures they had electroformed.

A few aircraft companies that have purchased electroformed nickel structures supplied property data for the electroformed material. These data, summarized in Table VII, show strength and ductility values that are about the same as many (but not all) of the values reported for nickel by the electroforming companies (Table VI).

Some individuals called attention to examples of inconsistency in the properties of the electroformed nickel supplied by a commercial source. For example, specimens from different areas of the same part varied considerably in mechanical properties:

- (a) 135,000-psi ultimate strength; 8 percent elongation
- (b) 55,000-psi ultimate strength; 30 percent elongation.

Microscopic examination of cross sections showed variations in grain structure and in occluded "dirt." The "dirt" particles resolved microscopically indicated a need for more effective solution filtration, which should be recognized as an important control factor. Variations in grain size and properties from one area to another probably reflect nonuniform agitation or current density. Current density (and wall thickness) should have been controlled within tolerable limits by using conforming or partly conforming anodes and/or current shields.

Some comments were received on ductility after welding or annealing, indicating that a sulfur-containing

addition agent was used in excess in the nickel electroforming bath. It was not established that the organization supplying the electroformed part was fully informed of the planned environment (temperature) or of the need for avoiding sulfur addition agents.

Representatives of some of the companies supplying electroformed structures described difficulties with contractors ordering the parts. In two or three cases, information and specifications were relayed on a piecemeal basis; complete drawings and specifications were delayed so long that delivery schedules could not be met, and costs skyrocketed because new requirements were introduced after tooling was completed. Communications between the purchasing arm and the engineering staff of some of the larger contracting companies also appeared to need improvement. Instances were described in which electroforming companies delivered prototypes of a structural part after absorbing all or part of the tooling costs in their general overhead, expecting to obtain orders for a large number of identical or similar components. Only later did they learn that property requirements and, sometimes, dimensional specifications had to be changed extensively. This made necessary extensive and costly changes in equipment and tooling. The electroforming of structural parts appears to be a marginal profit-making business. A chief reason has been the procedures adopted by contractors in subcontracting electroforming.

The total value of electroforming facilities in the hands of thirteen businesses with facilities for electroforming is about \$3,500,000. A large part of this total is undoubtedly devoted to the electroforming of molds, mirrors, and other nonstructural items. The facilities do not appear to match the potential demand for their use in making electroformed structural parts. However, officials of three of the larger organizations said that their facilities could be expanded 25 to 50 percent if the demand for structural items were increased.

Section IX. COSTS

The literature includes a few examples in which cost of structural parts was reduced by electroforming. For example, an \$8.10 unit cost for stamping and soldering small nickel chutes was reduced to \$0.85, by means of electroforming.⁷⁸ Air scoops costing \$344/unit when fabricated by bending and welding were electroformed in nickel, at first for \$239, later for \$185, and finally were purchased from an electroforming vendor for \$15.¹⁰⁰ A \$1700 cost for electroforming 20 hollow guide vanes represented a 66 percent cost reduction when compared with a \$5000 estimate for fabrication by bending and welding.¹⁰⁰ Costs for an air-intake lip were reduced 50 percent by adopting electroforming.¹⁰¹

In a survey conducted in 1962 on molecular forming procedures, typical total costs for electroforming simple shapes were estimated at about \$25 per pound of nickel.⁴¹ The estimate was misleading, because several structures have been electroformed at a much lower figure. Some single prototypes cost a great deal more

when tooling costs had to be charged to the production of just one part. Cost data supplied by vendors replying to questionnaires ranged from about \$2 to \$667 per pound of nickel. Three vendors reported examples of parts they had produced at <\$3 per pound of nickel, and another reported examples in the range of \$5 to \$9 per pound of nickel, including the tooling cost which was prorated over at least 100 parts in each case.

Some vendors evidently are not accounting costs accurately, judging by information received from personnel representing an organization asking for quotations on a 2-ft-long electroformed air duct. Quotations from four established sources were \$5.35, \$42, \$108, and \$275 per unit, not including tooling. Tooling cost estimates also spanned a broad range, from about \$600 to \$2000. The lowest quotation probably was not realistic. The highest might have reflected an anticipation of stringent specifications on dimensional tolerances and properties beyond the actual requirements.

Section X. CONCLUSIONS

The feasibility of commercially electroforming a variety of structural shapes with attractive properties for some missile and aircraft applications has been demonstrated. Some commercial sources have not demonstrated the good control of properties required for reproducing structures because some factors affecting properties have not been adequately controlled. The equipment and instrumentation for good control appears to be beyond the capital-risk capabilities of the organizations that have begun to supply electroformed structures.

The potential utility of electroforming for fabricating structures appears attractive and broad enough to justify an incentive program for encouraging and guaranteeing conformance with specified properties. A 90,000- or 100,000-psi minimum tensile strength for notch-insensitive electroformed nickel, and a minimum elongation of 5 or 6 percent, are now within the capabilities of several businesses, and could be encouraged in others.

Electroformed nickel or nickel-alloy structures with an ultimate tensile strength of about 200,000 psi or

more, an elongation of about 5 percent, and no notch sensitivity, appear within reach; but conditions affecting these properties, and procedures for controlling conditions to produce them, must be precisely identified. A development program appears desirable to establish the feasibility of controlling such a high-strength electroformed material and identifying how conditions should be controlled to reproduce such high-strength properties consistently. Such a program should include a study of the feasibility of accelerating the electroforming operation, which is relatively slow at the present time and requires two- or three-shift attention for structures with a wall thickness of 0.04 inch, or more.

Research supported by the Air Force may lead to the development of a practical procedure for electroforming an alloy with high strength at high temperatures (>1600 deg. F). However, there appears to be no emphasis in these programs on the development of a process for electroforming an alloy with very high strength ($>150,000$ psi) at room temperature.

Table I. EXAMPLES OF ELECTROFORMED STRUCTURES CITED IN THE ENGINEERING LITERATURE

Structure (a)	Dimensions, inches	Wall Thickness, inch	Metal or Alloy	Tensile Strength, 10 ³ psi	Insert or Grow-In	Dimensional Accuracy, inch	Surface Finish, rms microinches
Bulkheads ⁽⁹⁾	48 deep x 120 in diameter	0.014, 0.020, and 0.05	Nickel or nickel-iron alloy	90 to 160	None	—	16
Capsules ⁽¹⁰⁾	3/4 to 2 in diameter x 24 long	0.020 to 0.030	Nickel	Ca 110	None	—	40, outside
Compressive, discharge chambers ⁽⁹⁾	2 in diameter x 20 long	0.015	Nickel	Ca 110	None	0.005	Ca 15
Cones ⁽⁹⁷⁾	Ca 72 in diameter	1/4	Copper	32	Stainless steel support	—	35
Cylindrical shells ⁽⁴⁾	8 in diameter x 10 long	0.0045	Copper	—	None	0.005	(c)
Ducts ⁽⁹²⁾	6 x 6 x 3	0.030, 0.060	Nickel	80	Flanges	0.002 to 0.010	—
Expansion joints ⁽⁸²⁾	7 x 12 x 5	0.008 to 0.050	Nickel and nickel-cobalt alloy	80	None	—	—
Jet nozzles ⁽⁶⁾	3 to 6 in diameter x 36		Nickel	—	Spiral partitions between inner and outer shells	—	—
Parabolic panels ^(4, 20)	132 x 132	Ga 3/4	Nickel-copper composite	—	Fasteners	Very high precision	—
Pressure vessels ⁽⁴⁾	5 x 9	0.020	Nickel	>110	Stainless steel pressure fittings	—	—
Pressure vessels ⁽⁴⁾	3 1/2 (sphere)	1/4	Nickel	75 to 110	Nickel pressure fittings	0.015	15
Rings ⁽⁹⁸⁾	6 3/4 in diameter	0.050	Nickel	—	None	>0.002	8

Table 1. (Continued)

Structure (a)	Dimensions, inches	Wall Thickness, inch	Metal or Alloy	Tensile Strength, 10 ⁴ psi	Insert or Grow-In	Dimensional Accuracy, inch	Surface Finish, rms microinches
Rocket and venturi nozzles ^(18, 84, 81)	0.2 to 1 3/4 in diameter x 8 long	Ca 0.04	Cobalt-35% tungsten alloy and Co-W-Ni-Fe alloy	86 to 95	Ribs for cooling passages	—	—
Sandwich panels ^(28, 80, 81)	12 x 12	Ca 0.02	Nickel	Ca 110	Electroformed hyperbolics	—	—
Shields ⁽²⁸⁾	252 long	0.006 to 0.012	Nickel	—	None	—	—
Solar concentrators ^(17, 80, 108)	60 in diameter	0.002 to 0.010	Nickel	—	Fittings and turns	0.003 to 0.005	—
Solar collector and frame (Fresnal) ^(11, 47)	5 x 16 segments	0.002 to 0.003	Nickel	Ca 110	None	High precision	2 to 3 inside
Tubing with internal fins ⁽¹⁷⁾	3 in diameter x 66 long	3/4	Copper	—	Copper disks	—	—
Tubing, thin-walled for heat exchangers ⁽¹⁰⁸⁾	3/4 in diameter x 6 long	0.003	Nickel	Ca 115	None	—	—
Tunnels (nozzles) ⁽⁴⁷⁾	3 to 24 in diameter x 142 or 192	3/4	Nickel	—	(g)	0.001 or 0.002	8 inside, 12 or 36 outside
Wing tips ⁽⁸¹⁾	1 3/4 x 16	0.020 ±0.002	Nickel	—	None	0.002	>16

(a) Numbers in parentheses refer to references listed at the end of this report. Other structural components described with incomplete detail in the literature included angles⁽⁸⁸⁾, nickel or nickel-cobalt-alloy bowls (30 inches in diameter with a wall thickness of 3/4 to 1/2 inch)⁽¹¹⁴⁾, channel⁽¹⁰⁷⁾, chutes⁽⁸⁸⁾, corrugated expandable baffles, cutters, floats, fuel injectors, funnels⁽⁸⁴⁾, nickel-cobalt-alloy gages (3/4 inch thick), stone guards⁽⁸⁷⁾, struts, switches plates, shadow masks, screen, wedges, and wind-tunnel sections⁽¹⁰⁸⁾.

(b) Expandable diaphragms for Centaur, which included an integrated, annular diaphragm expansion ring^(8, 14, 87).

(c) The influence of surface imperfections on buckling loads was determined⁽¹⁷⁾.

(d) Vessels consisting of a 0.020-inch-thick layer of nickel, 1/2 inch of foamed latex, and an outer, 0.030-inch-thick layer of nickel^(80, 81, 112).

(e) Testing to bursting with air pressure. A vessel electroformed in nickel with a tensile strength of about 100,000 psi burst with a pressure of 29,000 psi which was nearly equal to the burst strength calculated from tensile data. Burst strength with a softer nickel was 20,810 psi. Failure occurred at the joint of the grown-in fitting at a pressure of about 16,000 psi for two other vessels⁽⁸⁸⁾.

(f) Stress free, dimensionally stable, and vacuum tight^(88, 87).

(g) Tubing was inserted between two layers in some models; beryllium-copper-alloy throats were grown in others^(12, 15, 100, 108, 111).

(h) Bolt holes were accurately located for interchangeability^(8, 88).

Table II. STRUCTURAL COMPONENTS ELECTROFIED COMMERCIALY OR IN PILOT-PLANT FACILITIES

Company	Examples of Components	Dimensional Accuracy			Finish, rms microinches		Electroformed Metal	Inserts or Grow-Ins	Contour Limitations	
		Wall Thickness, per cent of specified thickness	Length and Width, inch	Roundness, inch	Mandrel Side	Outer Surface			Min. Radius for Inside Corners, inch	Max Depth to Width Ratio of Recesses (a)
Allied Research and Eng. Co	Air scoops, ducting, pressure vessels, nozzles	5	0.0001	<32	32		Nickel, nickel-cobalt alloy	Rockets, vanes	None	2
Astro Systems	Rocket engine injectors and liners	4	Ca 0.002	4	125		Nickel	Cooling passages	—	5
Bart Manufacturing Co.	Bulkheads, jet nozzles, panels, reflectors, wing tips	5 to 15	<0.001 to 0.003	<1 to 32	60 to 100		Copper, nickel	Brackets, fittings	Same as required thickness	1
Camin Laboratories, Inc.	Manifolds, nozzles	10	—	2	—		Nickel	Bushings, flanges	0.020	5
Chromium Corp. of America	Belts, bellows, spars	—	—	<1	—		Nickel	None	—	—
Columbia Records, Cryon Precision Products Div.	Bulkheads, pressure vessel liners	5	0.005	<1	Ca 30		Copper, iron, nickel	—	—	1/2
Dynaflex Corporation	Cones, ducting, hemispheres, nozzles, pressure vessels	—	<0.001	4 to 16	4 to 32		Copper, nickel, gold	Iris, diaphragms	Same as required wall thickness	—
Electroforms, Inc.	Bulkheads, hemispheres, pressure bottles, duct	10 to 25	0.001 to 0.01	2 to 125	125		Nickel	Flanges, baffles, fittings	0.005	4
Electro-Optical Systems, Inc.	Solar concentrators, shields, tubes	5 for 0.060-inch wall	—	<1	4 to 125		Copper, nickel	Tori, ribs	>required wall thickness	—
Gar Precision Products	Air intake covers, nozzle cones	10	0.001	16	—		Nickel	Flanges, corner angles	None	1
General Dynamics Corp. Ft. Worth Division	Ducts	—	0.003	5 to 25	—		Nickel	Baffles, fittings, tabs	0.060	1
Astronautics Division	Camshafts	10	0.001 to 0.002	>32	>32		Copper, nickel	None	—	—
General Electric Co. Jet Engine Corp.	Air scoops, inlet guide vanes, jet nozzles	—	—	—	30 to 80		Nickel, Ni-Mn alloy	Baffles, trunnions	—	—
General Motors Corp. Allison Division	Combustion chambers, discharge tubes	22	0.004 to 0.005	15 to 20	—		Nickel	—	—	—
General Technical Corp.	Pilot tubes, structural wave guide	1 to 5	0.001 to 0.005	2 to 64	16 to 32		Nickel	Baffles	>0.040	—
LTV Vought Aircraft Co.	Deflectors, periscope tubes, wind tunnel models	5	0.003 to 0.010	16 to 32	16 to 64		Copper, nickel	—	—	1/2
Plating Engineering Co.	Wind tunnel parts, bellows, couplings	About 20	0.005	10	—		Copper, nickel	Pins	0.030	1
United States Rubber Co.	Fuel containers, plates	—	—	—	—		Nickel, copper	—	0.005	1

(a) For electroforming at very low current densities (about 5 amp/sq ft), the maximum depth-to-width ratio can be less than the practical maximum ratio for normal current densities. The relatively high ratios cited by some organizations probably reflect experience with low current densities (and low electrodeposition rates).

Table III. PHYSICAL PROPERTY DATA FOR ELECTROFORMED METALS

Metal	Density (lb/cu in)		Modulus of Elasticity (10 ⁴ psi)	Electrical Resistivity (microhm-cm)	Coefficient of Linear Expansion Near Room Temp (microinch/F)
	Minimum	Maximum			
Cobalt, 35% tungsten alloy(19,94)	—	0.457	—	100	4.8
Copper(4,37,84,85,87,93)	—	0.323	13,000 to 16,900	1.7	9.2
Nickel(17,49,50,51,94,97)	0.321	0.327	23,000 to 28,000	7.4 to 10.9	3.1 to 6.3
Iron(33)	—	0.284	30,000	9.9	6.7

Table IV. STRENGTH AND DUCTILITY OF ELECTROFORMED METALS AND ALLOYS AT ROOM TEMPERATURE

Electroformed Metal or Alloy	Ultimate Tensile Strength (10 ⁴ psi)			Yield Strength (10 ⁴ psi)			Elongation in 2 Inches (per cent)(a)		
	Typical or Nominal	Minimum	Maximum	Typical or Nominal	Minimum	Maximum	Typical or Nominal	Minimum	Maximum
Aluminum(b)	13	12	14	—	—	—	7	1	10
Cobalt, 30% tungsten alloy(30)	110	107	157	—	—	—	—	—	—
Cobalt, 28 to 35% tungsten alloy, heat treated(22,116)	100	92	131.3	74	—	—	1	0	1
Cobalt, 35% tungsten, 1% nickel, 3% iron alloy, heat treated(19,20)	100	93	105	—	—	—	—	—	—
Copper(11,4,37,62,66,84,86)	30	10	80	13	12	15	25	5(c)	50
Copper, annealed (1200 F)(17,44)	29	26	37	6	—	—	45	30	63
Iron(31,65)	55	37	78	—	—	—	3	0.5	40
Nickel(d)	90	51	214	65	32	91	10	2	37
Nickel, annealed(8,99,108)	50	50	55	12	10	16.8	—	—	44
Nickel, 40% cobalt alloy(27),(e)	150	100	206	—	—	—	2-4	1	15
Nickel with 1 to 4% dispersed alumina, annealed at 1475 F(98)	—	—	—	40	21	42	—	—	—
Nickel, 2% cobalt alloy, annealed(27)	50	50	—	—	—	—	20	—	20

(a) Reduction in area.
 (b) Battelle Memorial Institute unpublished data for aluminum electroformed in the organo aluminum hydride bath(10).
 (c) Some copper disks electroformed with high speed rotation exhibited an elongation of only 1 percent(10).
 (d) References for nickel are given in Table V.
 (e) Battelle Memorial Institute unpublished data.

Table V. PROPERTIES OF ELECTROFORMED NICKEL AT ROOM TEMPERATURE^(a)

Electroforming Bath	Density (lb./cu. in.)	Tensile Strength (10 ³ psi)	Yield Strength (10 ³ psi)	Elongation in 2 Inches (percent)
Nickel chloride	0.331 ^(a) 0.328 to 0.320 ^(a)	108 to 124 ^(a) 98.9 ^(a) 88 to 137 ^(a) 100.2 to 112 ^(a)	90.5 to 91.5 ^(a) — — 72.8 to 80.8 ^(a)	8 ^(a) 21 ^(a) 5 to 15 ^(a) 5 to 15½ ^(a) 16.6 ^(a) 32.0 ^(a) 22 to 30 ^(a)
Nickel fluoborate ^(a)	0.314 to 0.331 ^(a) 53.5 ^(a)	74.5 ^(a) 62 to 69 ^(a)	— —	— —
Nickel sulfamate ^(a)	0.332 ^(a) 0.323 to 0.328 ^(a)	111 to 119 ^(a) 108 ^(a) 102.0 ^(a) 116 ^(a) 85 to 152 ^(a) 90 to 111 ^(a) 94 to 108 ^(a) 60 to 100 ^(a) 60 to 120 ^(a)	73.5 to 78.5 ^(a) — — — 60.8 to 93.3 ^(a) 68.7 to 78.5 ^(a) — — —	11 to 14 ^(a) 15 to 20 ^(a) 14 ^(a) — 5.6 to 12.0 ^(a) 6.6 to 7.0 ^(a) 3.5 to 5.0 ^(a) 5 to 30 ^(a) 6 to 30 ^(a) 2.5 to 11.5 ^(a)
Nickel sulfamate ^(a)	0.320 to 0.327 ^(a)	109.6 to 145.2 ^(a) 155 ^(a) 80.6 to 202 ^(a) 101 to 112 ^(a) 174 to 214 ^(a) 74.2 to 74.7 ^(a) 66.1 to 68.6 ^(a) 63.9 to 64.5 ^(a) 54.3 ^(a) 50 ^(a)	71.3 to 104.5 ^(a) — 102 to 115 ^(a) 67.8 to 71.5 ^(a) 97 to 128 ^(a) 51.3 to 51.6 ^(a) 45.8 to 48.5 ^(a) 38.6 to 38.7 ^(a) 16.8 ^(a) —	— — 6.5 to 7.8 ^(a) 5.6 to 7.0 ^(a) 0.7 to 5 ^(a) 15 to 16 ^(a) 19 to 23 ^(a) 33 to 34 ^(a) 44.2 ^(a) —
Nickel sulfamate, annealed at 600 F	—	—	—	—
Nickel sulfamate, annealed at 700 F	—	—	—	—
Nickel sulfamate, annealed at 7000 F	—	—	—	—
Nickel sulfamate, annealed at 1250 F	—	—	—	—
Nickel sulfamate, annealed at 1500 F	—	—	—	—
Watts type (nickel sulfate and nickel chloride) ^(a)	0.327 to 0.331 ^(a) 0.329 to 0.332 ^(a)	57.8 to 63.9 ^(a) 56.0 ^(a) 56 to 105 ^(a) 58 to 156 ^(a) 130 to 150 ^(a) 51.0 ^(a) 53 to 62 ^(a) 35 to 39 ^(a)	32.4 ^(a) — — 33 to 118 ^(a) — — — —	27 to 35 ^(a) 28 ^(a) 17 to 37 ^(a) 4 to 31 ^(a) 5.7 ^(a) 30 ^(a) 35 to 39 ^(a) 23 to 37 ^(a)
Watts type, annealed at 750 F	—	—	—	—
Watts type, annealed at 1850 F	—	—	—	—

(a) Values for nickel electroformed in solutions containing no additive agents.
 (b) Values for nickel electroformed in solutions containing 0.01 percent sulfur, or more, to the nickel.
 (c) Values for nickel deposited on specially prepared surfaces in Watts-type solution with a high pH (5.0) and maintained at a low temperature (110 deg. F).^(a)

Table VI. CAPACITY DATA FOR ORGANIZATIONS WITH ELECTROFORMING FACILITIES

Company	Metal	Maximum Size, feet		Maximum Wall Thickness, inch	Typical Mechanical Properties (a)		Electrodeposition Rates, inch/hour	Value of Present Facilities, dollars
		Present Facilities	Projected Facilities		Ultimate Tensile Strength, 10 ³ psi	Elongation, per cent		
Allied Research and Eng. Co.	Nickel, nickel-cobalt alloy	6 x 12	30 x 30	1½	100 (nickel)	10	0.004 to 0.020	100,000
Astro Systems	Nickel	1 x 2 x 3	12 x 12	½	75.95 (nickel)	15-20	—	10,000
Bart Manufacturing Company	Copper, nickel	4 x 12 x 12	—	¾	55 to 200 (nickel)	½ to 20	0.001 to 0.002	1,500,000
Camin Laboratories, Inc.	Nickel	2 x 2 x 5	—	½	—	—	0.002 to 0.010	150,000
Chromium Corp. of America	Nickel, cobalt-tungsten	4 x 25	—	¾	76 (nickel)	15	0.001 to 0.005	—
Columbia Records—Cryton Precision Products Div.	Copper, iron, nickel	4 x 10 x 10	12 x 12	½	128 (nickel)	10	to 0.010	750,000
Dynatex Corporation	Copper, nickel, gold	3 x 7½ x 7½	—	¾	—	—	0.301 to 0.010	175,000
Electroforms, Inc.	Nickel	9 x 9, 4 x 17, or 12-in diameter	17 x 17	>2½	85 to 200 (nickel)	10 to 30	0.0005 to 0.010	200,000
Electro-Optical Systems, Inc.	Copper, nickel	10 x 10 or 4 x 20	30 x 30	¾	—	—	0.0001 to 0.005	—
Gar Precision Products, Inc.	Nickel	3½ x 3½ x 7	5 x 23	—	110 (nickel)	10	0.0005 to 0.005	500,000
General Dynamics Corp.—Astronautics Division	Copper, nickel	1½ x 1½	—	0.016	—	—	0.0008 to 0.0015	1,500
Ft. Worth Division	Nickel	6 x 6	—	½	60 to 109 (nickel)	10	0.001 to 0.0025	—
General Electric Company (Syracuse) ^(a)	Copper, nickel, nickel-iron alloy	1 x 1½	1½ x 3	½	—	—	0.002 to 0.004	(b)
Jet Engine Division	Nickel, nickel-manganese alloy	2 x 4 x 4	—	½	to 120 (nickel)	—	0.001 to 0.0015	—
General Technical Corporation	Copper, nickel	3¾ x 6	12 to 15 in diameter	—	100 to 200 (nickel) 160 to 200 (tungsten-flament reinforced copper)	—	0.002 to 0.004	40,000
K. C. Jones Plating Co.	Copper, nickel	2½ x 5½ x 6	—	¾ ^a	—	—	0.001 to 0.006	18,000
Plating Engineering Co.	Nickel	3 x 9	4 x 9	½	60 to 80 (nickel)	25	0.0005 to 0.003	50,000
Savage-Rowe Plating Co.	Copper, nickel, nickel-cobalt alloy	3 x 3 x 6	—	¾	—	—	—	—
Soni-Recording Products	Nickel	2½ x 10	—	—	—	—	—	50,000
U.S. Rubens Company	Copper, nickel	2 x 4 x 11½	—	½	60 (nickel)	20	—	>50,000

(a) Refers in most cases to metal with a wall thickness of 0.02 to 0.04 inch.

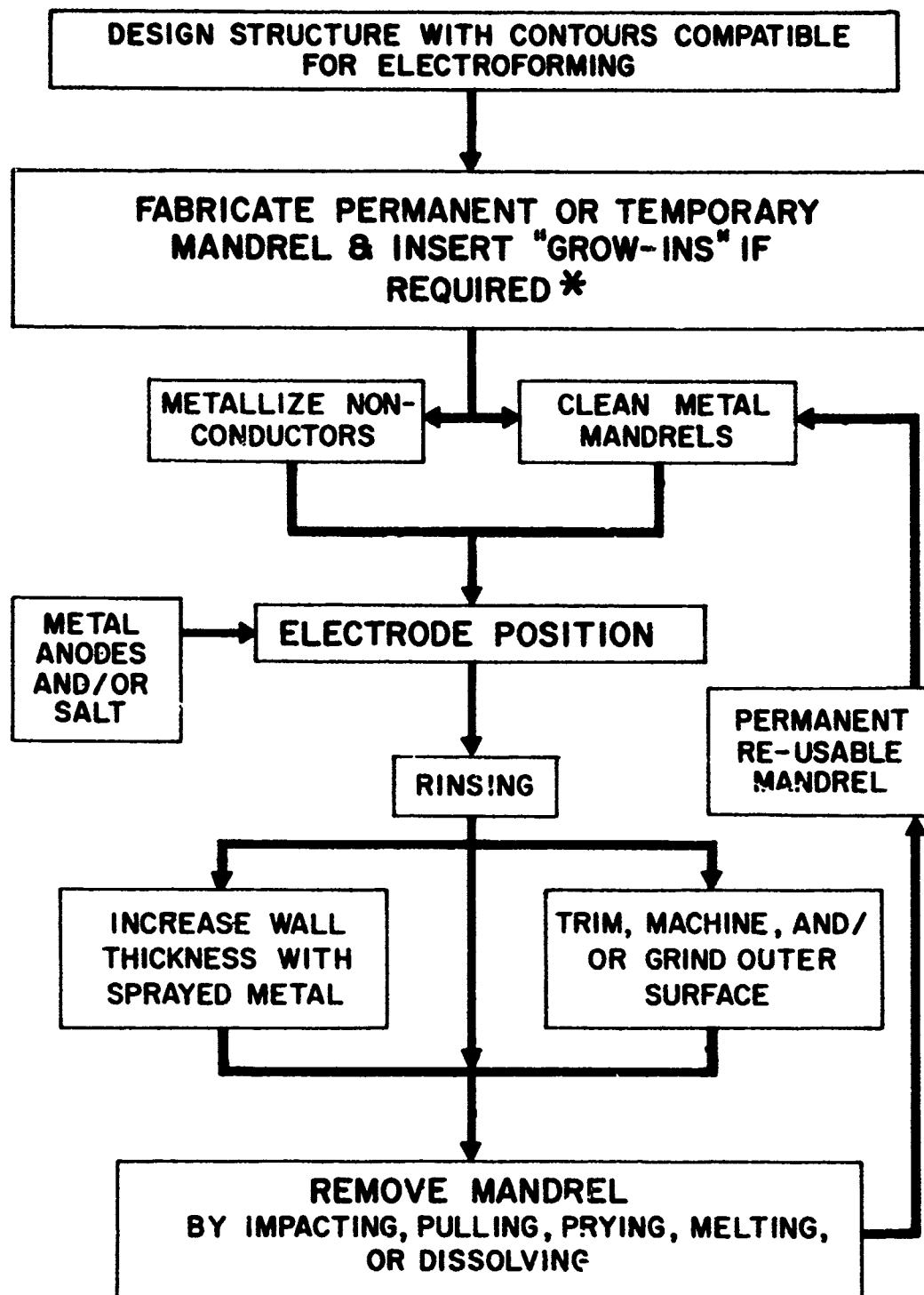
(b) Experimental facilities.

Table VII. PROPERTY DATA FOR ELECTROFORMED NICKEL STRUCTURES FROM PURCHASERS OF ELECTROFORMED NICKEL PARTS

<i>Company</i>	<i>Components</i>	<i>Tensile Strength, 10⁴ psi</i>	<i>Yield Strength, 10⁴ psi</i>	<i>Elongation in 2 Inches, per cent</i>	<i>Dimensional Wall Thickness, per cent of specified thickness</i>	<i>Required Dimensional Accuracy, Length and Width, inch</i>	<i>Finish Requirement, rms microinches</i>
North American Aviation, Los Angeles Division	Ducting	80 and 90	50 and 60	10	20	$\frac{1}{32}$	125
Rocketdyne Division	—	100 ^(a)	—	10	—	—	—
Marquardt Corporation	Air-inlet ducts, nozzles	100 and 125	65 and 80	7 to 15	20	—	—
Northop-Norair	Air-intake lips, manifold ducts ^(b)	80 to 90	55 to 60	9 to 10	10 to 15	0.040	125

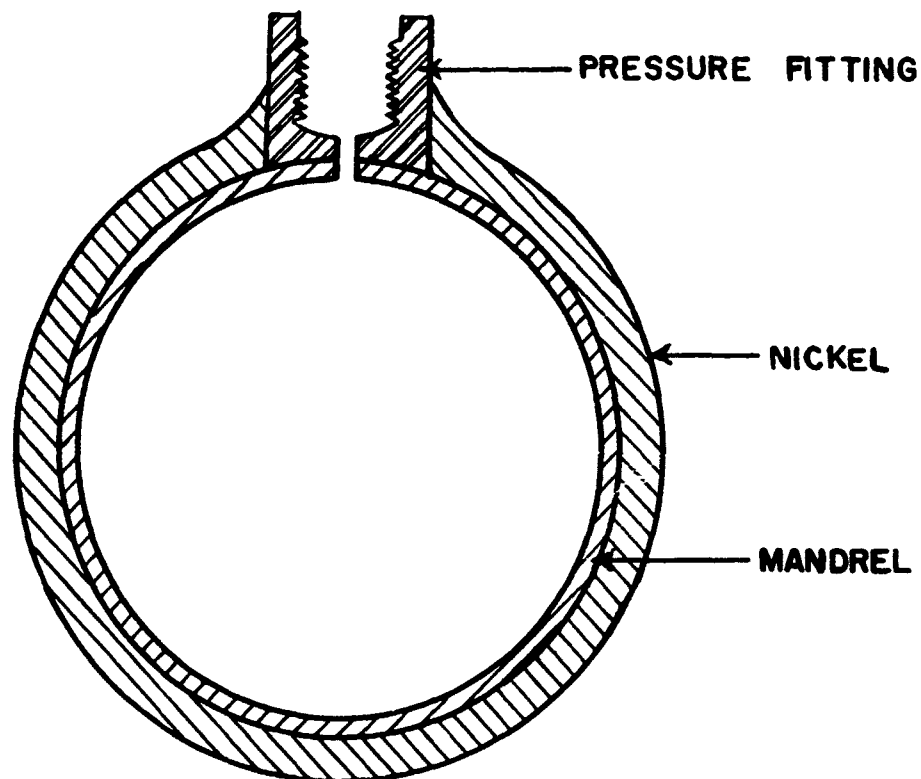
(a) Tensile strength at -423 F, 163,700 psi; yield strength, 96,500 psi; elongation, 11 per cent.

(b) Designed for calculated stresses of 75,000 and 60,000 psi.

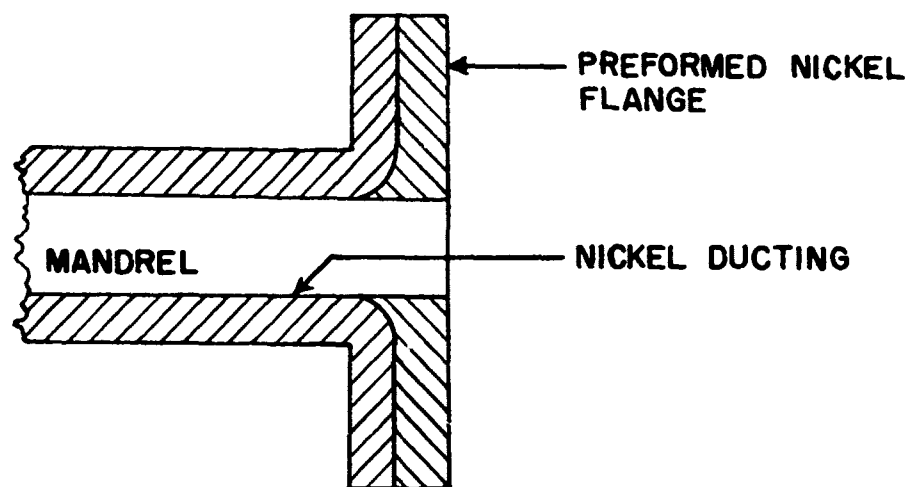


*GROW-INS ARE ILLUSTRATED IN FIGURES 2 AND 3

FIGURE 1. MAJOR OPERATIONS FOR ELECTROFORMING A TYPICAL STRUCTURE



SKETCH A. PRESSURE VESSEL



SKETCH B.

FIGURE 2. SKETCHES OF ELECTROFORMED NICKEL STRUCTURES WITH PREFORMED INSERTS

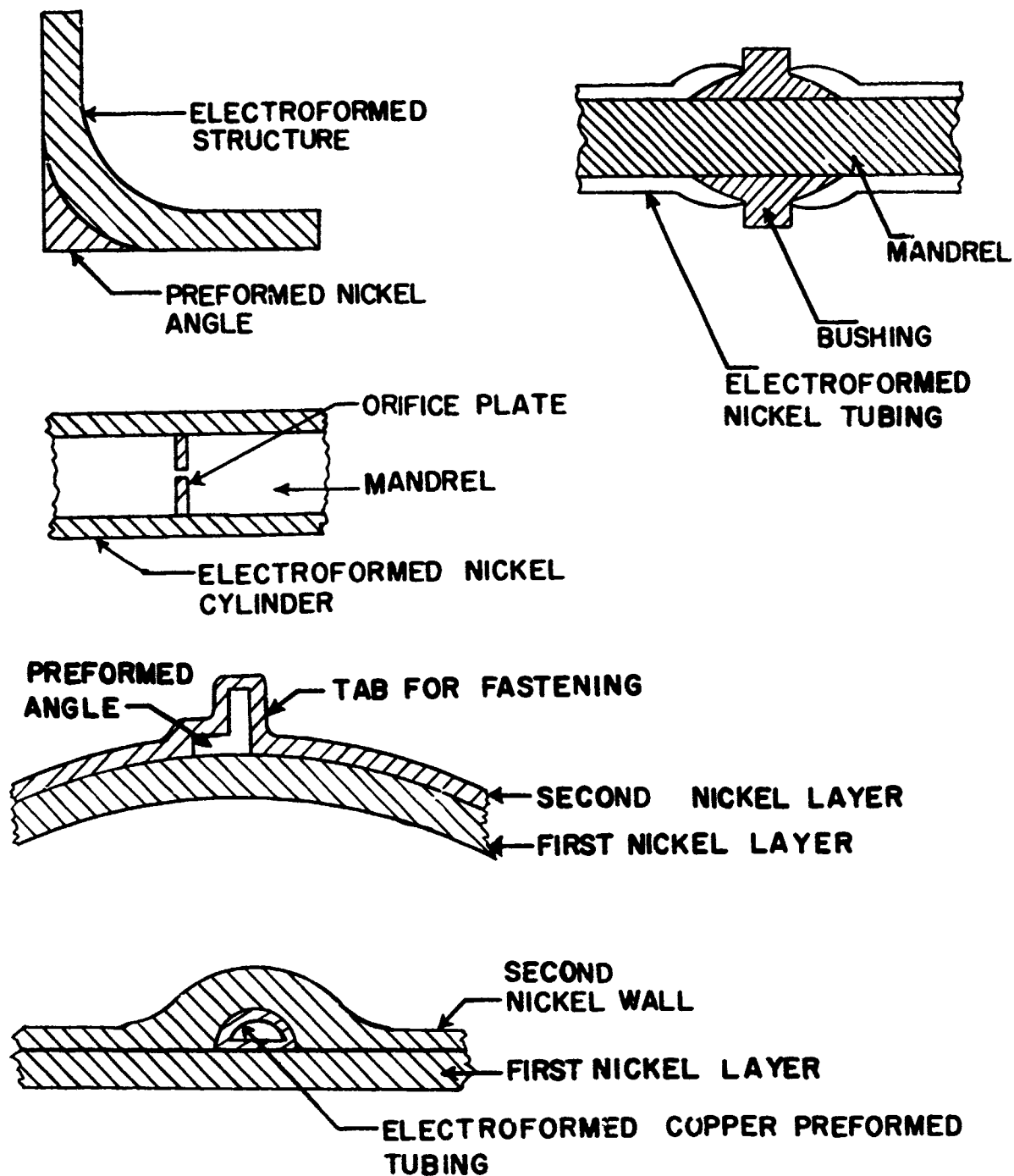


FIGURE. 3 SECTIONS OF ELECTROFORMED STRUCTURES WITH GROWN-IN INSERTS

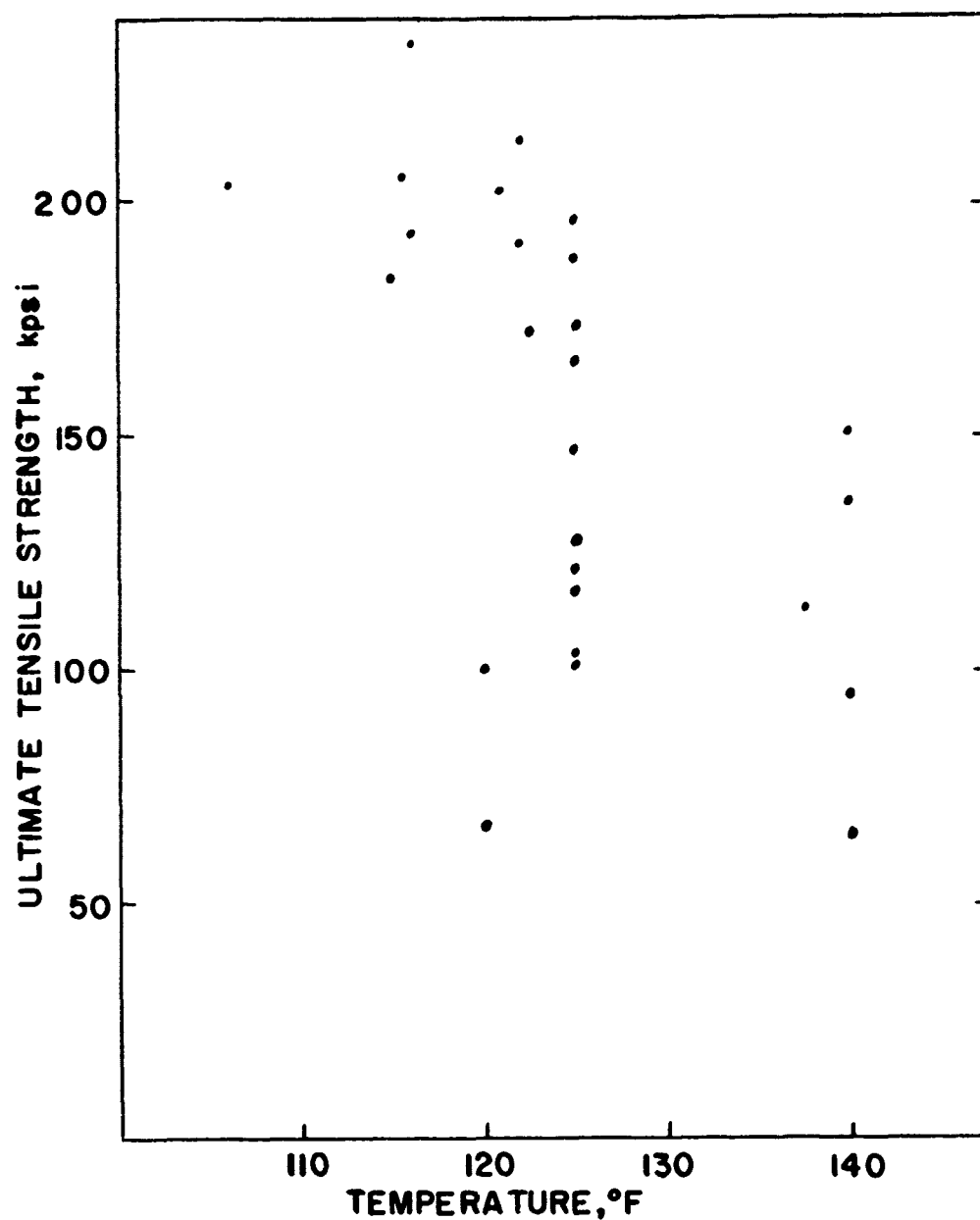


FIGURE 4. ULTIMATE TENSILE STRENGTH OF NICKEL ELECTROFORMED IN NICKEL SULFAMATE SOLUTION CONTAINING STRESS REDUCER AS A FUNCTION OF THE TEMPERATURE OF THE ELECTROFORMING BATH

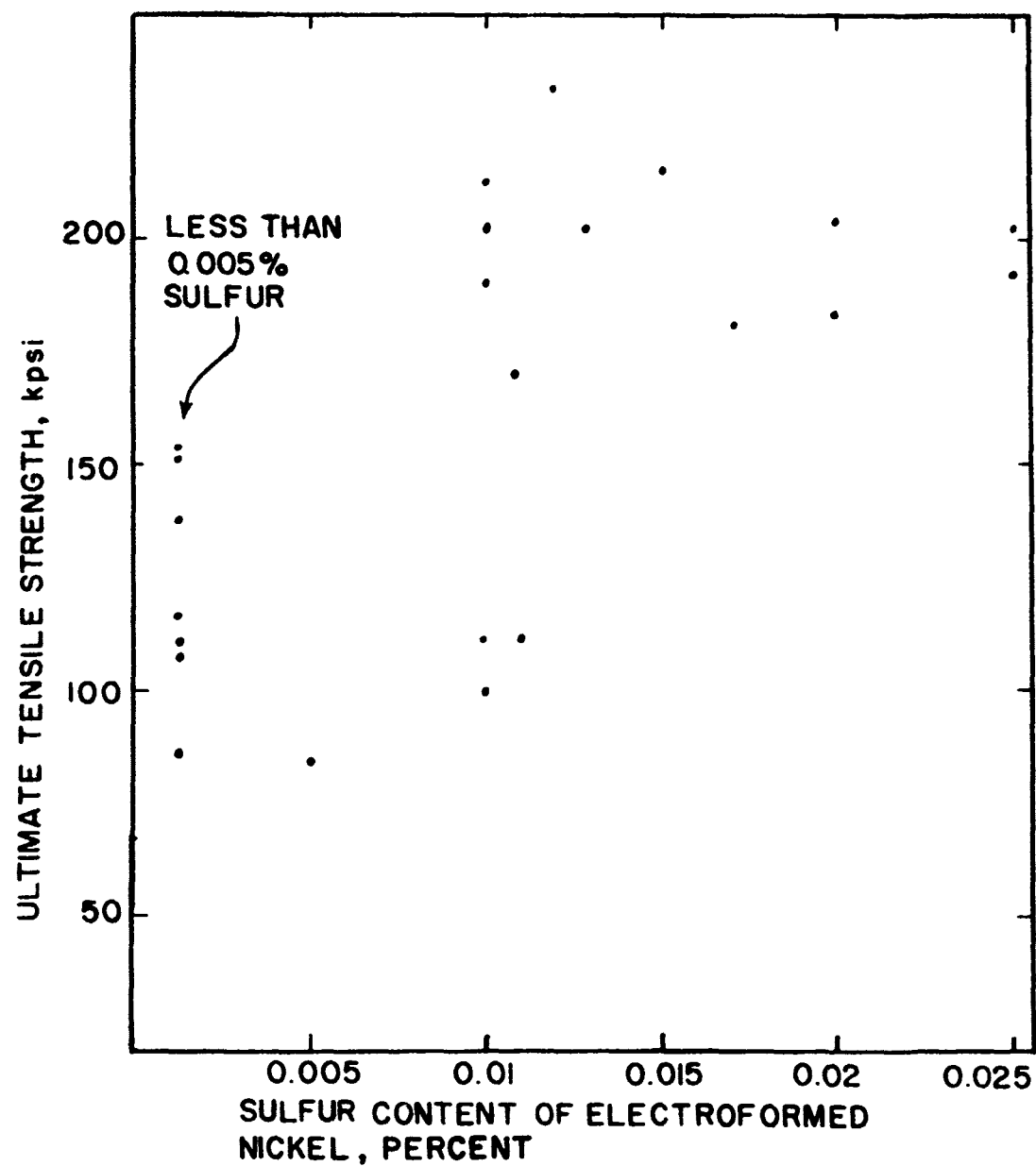


FIGURE 5. ULTIMATE TENSILE STRENGTH OF NICKEL ELECTROFORMED IN A NICKEL SULFAMATE BATH AT 115 TO 125°F AS A FUNCTION OF THE SULFUR CONTENT OF THE NICKEL

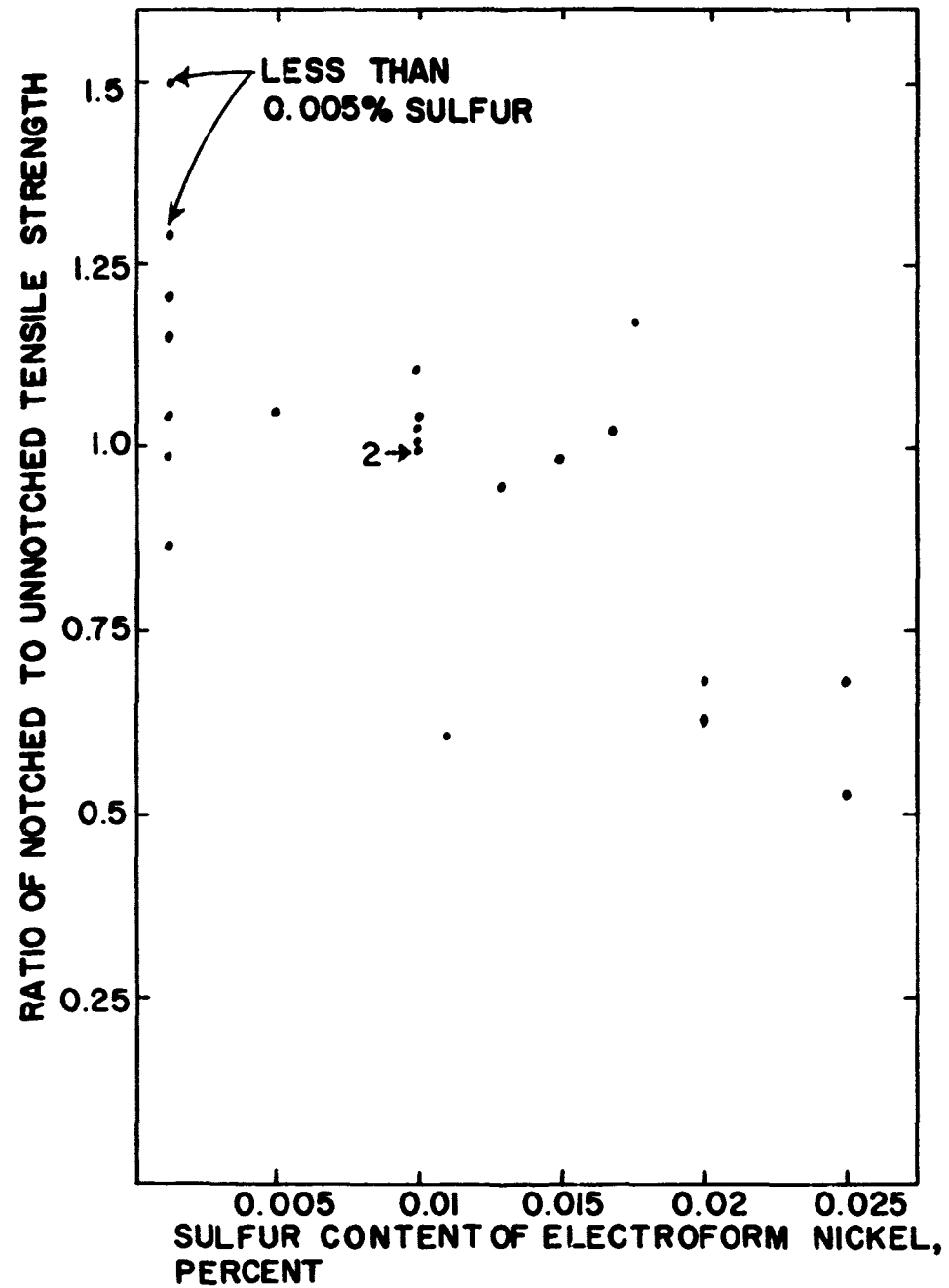


FIGURE 6. RATIO OF NOTCHED AND UNNOTCHED TENSILE STRENGTH, AS A FUNCTION OF THE SULFUR CONTENT OF NICKEL ELECTROFORMED IN NICKEL SULFAMATE BATH. ($K_t=6.3$ for the notched specimens.)

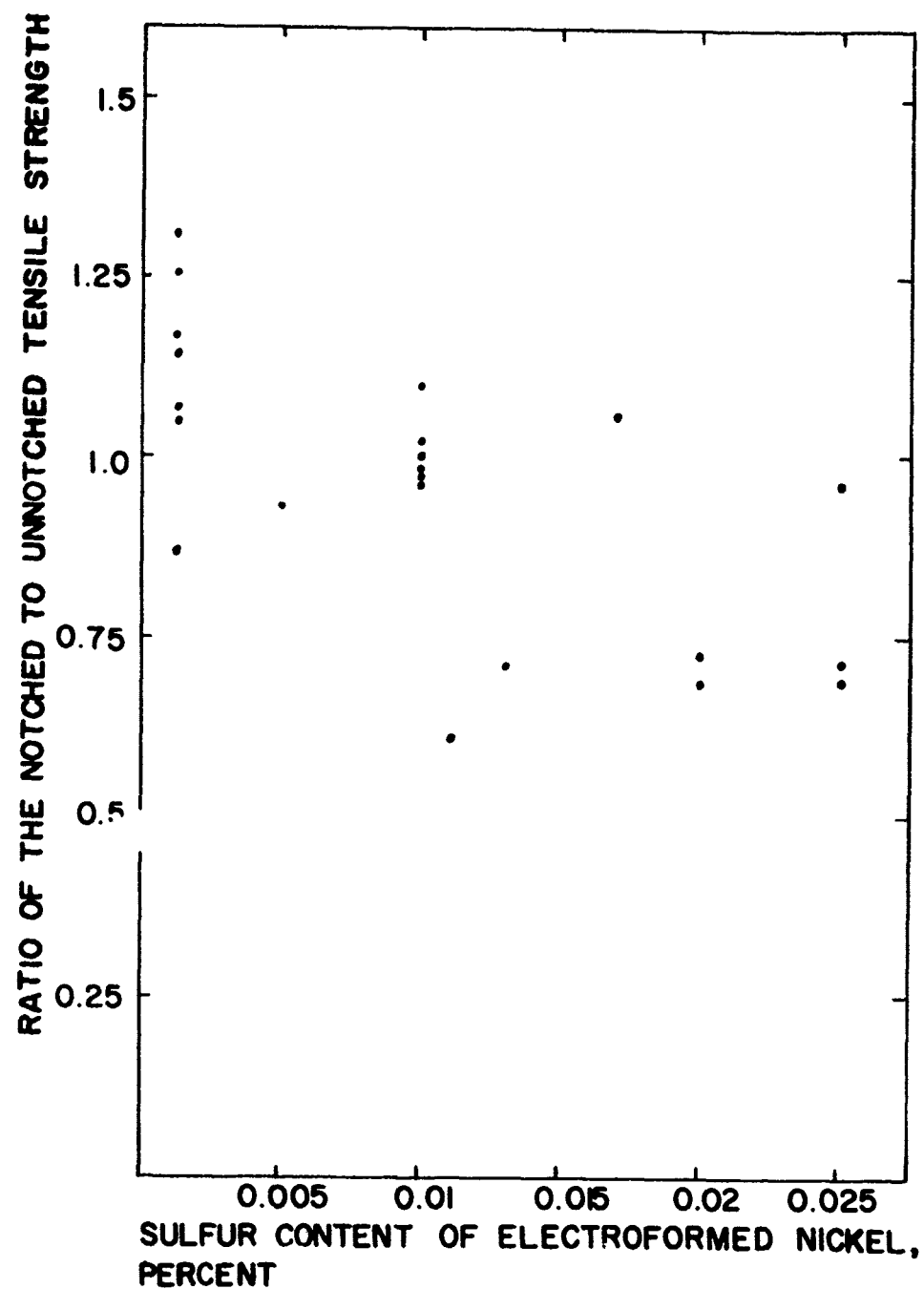


FIGURE 7. RATIO OF NOTCHED AND UNNOTCHED TENSILE STRENGTH AT -423°F , AS A FUNCTION OF THE SULFUR CONTENT OF NICKEL ELECTROFORMED IN NICKEL SULFAMATE BATHS.
($K_1 = 6.3$ for the notched specimens)

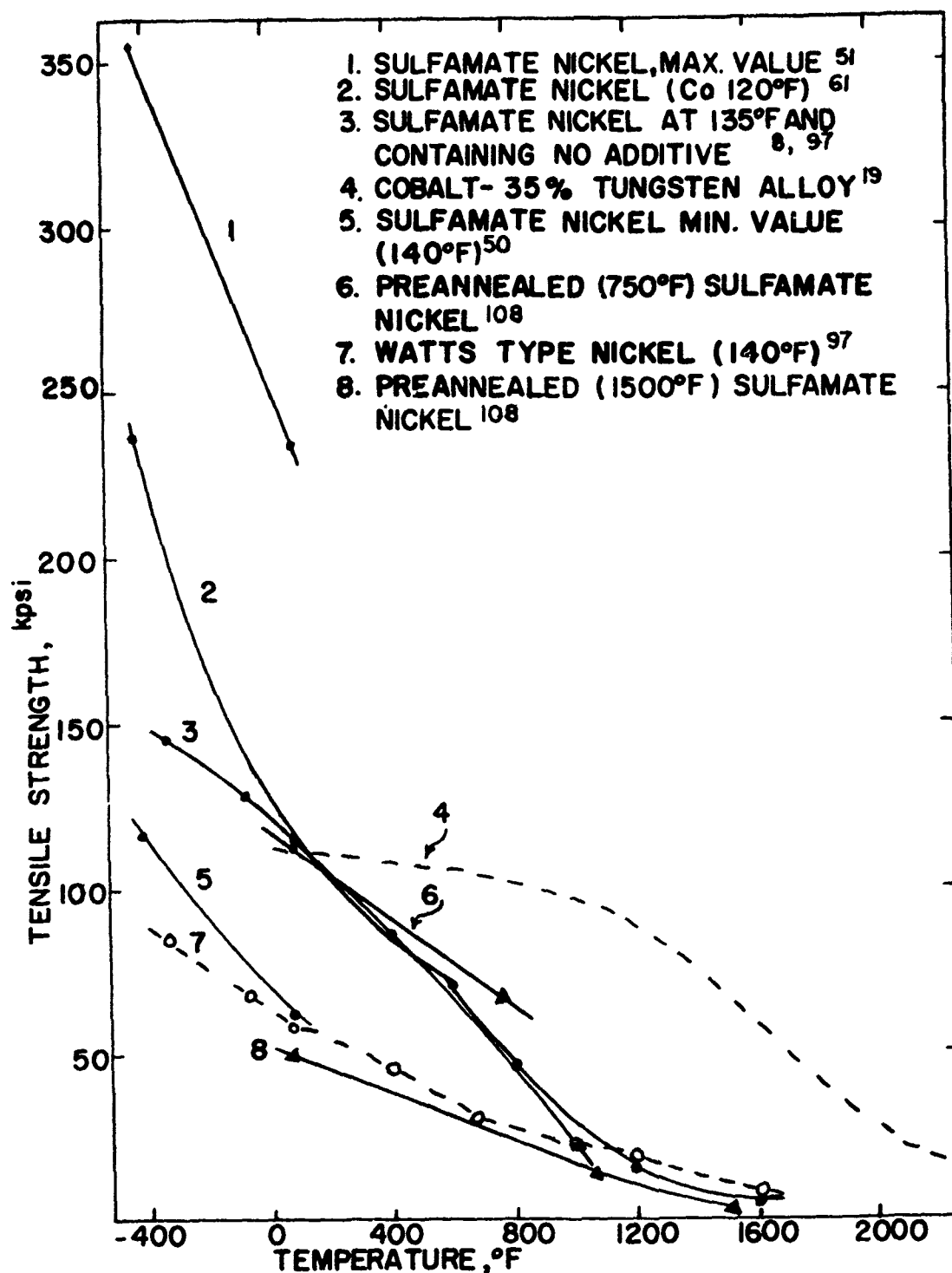


FIGURE 8. ULTIMATE TENSILE STRENGTH OF ELECTROFORMED NICKEL AND COBALT TUNGSTEN ALLOY AT LOW AND HIGH TEMPERATURES

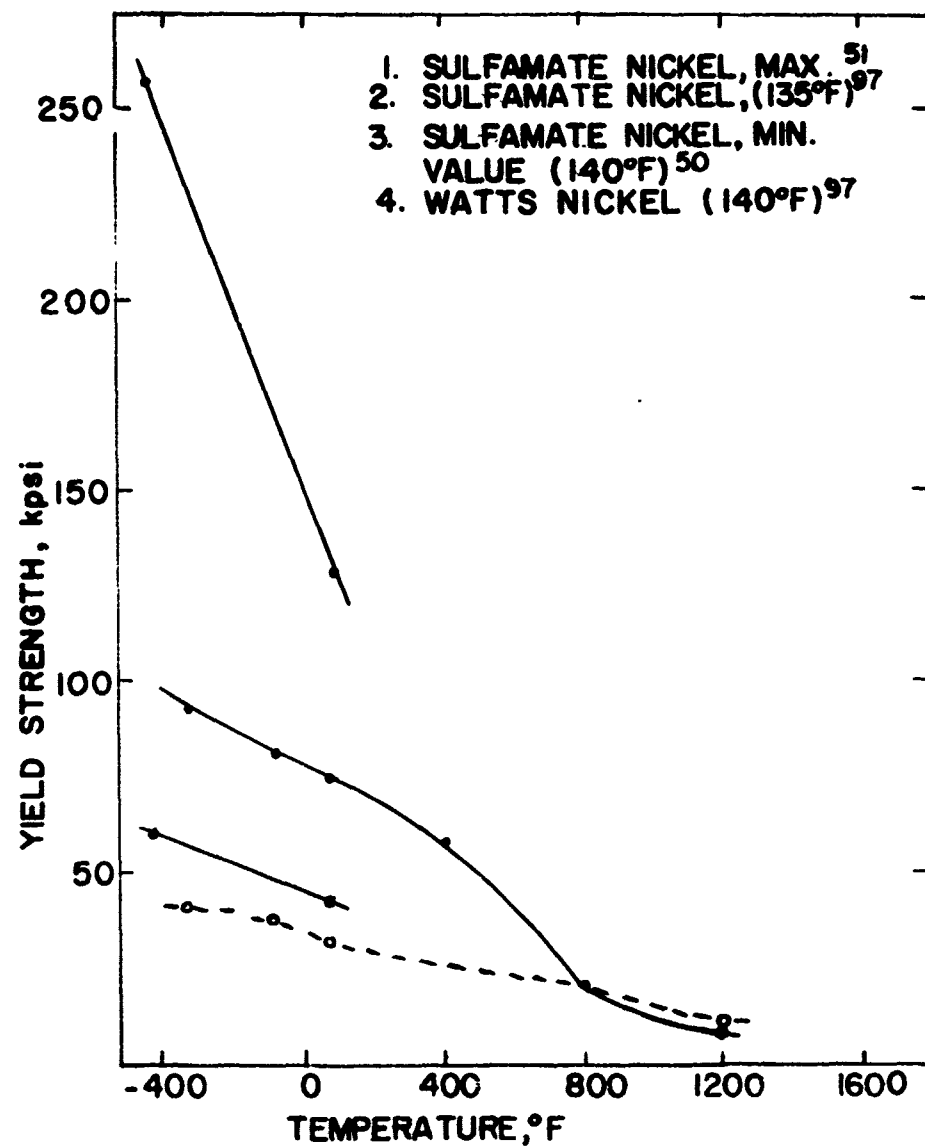


FIGURE 9, YIELD STRENGTH OF ELECTROFORMED NICKEL AT LOW AND HIGH TEMPERATURES

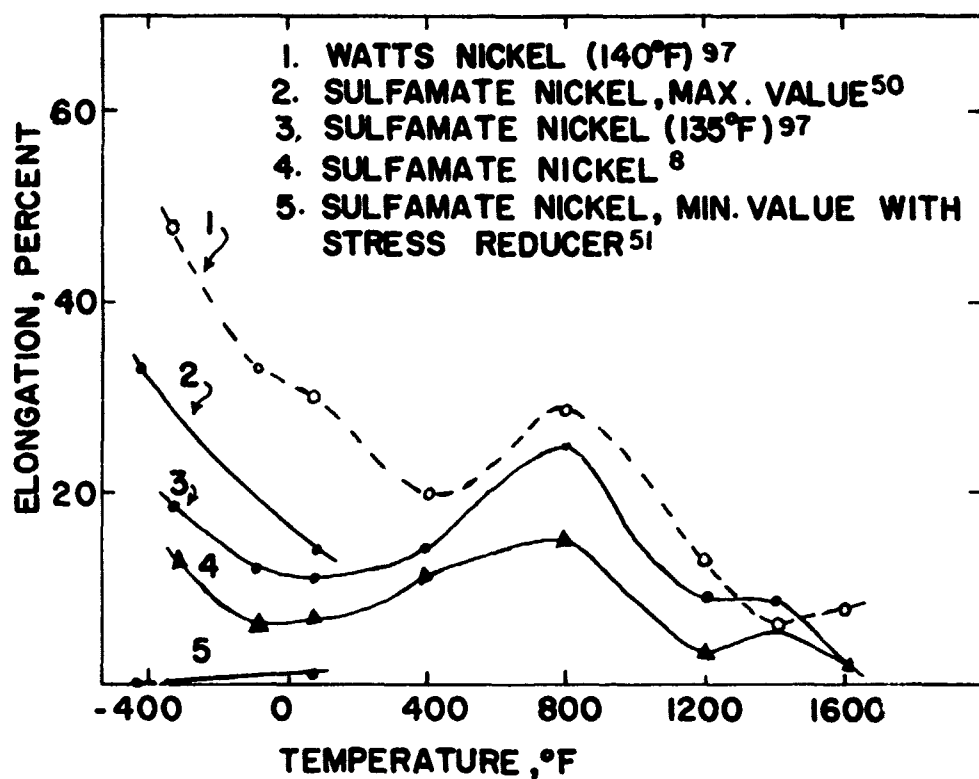


FIGURE 10. ELONGATION OF ELECTROFORMED NICKEL AT LOW AND HIGH TEMPERATURES

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